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# Acknowledgments

The organization of the Architectural Engineering Institute (AEI) Conference 2013 was different from previous AEI conferences in that AEI decided to have a university with an Architectural Engineering program host the conference. This AEI 2013 conference is therefore a new experience being tried for the first time at Penn State University hosted by the Department of Architectural Engineering. It is hoped that this experience has proved successful and the experience will help and contribute to the organization of future AEI conferences.

The organization of the AEI 2013 conference relied on the contribution of many people. Starting with the conference steering committee, we would like to acknowledge the contribution of Mohammad Ettouney, Tom Babacz, Scott Campbell, Abe Lynn, Mike McGeen, Chuck Meyer, Brian Noonan, Jay Puckett, Thanos Tzempelikos, Filza Walters, and John Zacher in guiding the directions for the technical content of the conference. Next, the contribution of the scientific committee in promoting the conference and offering help in the review process is acknowledged. The support and contribution of several Penn State Architectural Engineering Department faculty, including Kevin Parfitt, Kevin Houser, Robert Holland, Robert Leicht, and Steve Treado for participating in the local organizing committee and helping in the planning and inviting authors to submit papers is acknowledged. Next the significant contribution of the AEI staff Jennifer Balsley (former Manager), Verna Jameson, and Jim Rossberg (Managing Director of ASCE Engineering Programs) is gratefully acknowledged. Last but not the least, the organization of this conference would not have been possible without the impressive hard work of AE Department staff Nancy Smith and Nancy Sabol.

Many other individuals have contributed in planning special programs such as workshops, short courses, and committee meetings. The contribution of all those who have helped is acknowledged. However, the one special event that has taken great effort is the ASCE Charles Pankow Annual Architectural Engineering Student Competition that takes place every year during AEI conferences (AEI Technical Conference and AEI Student Conference). The Chair of the committee overseeing this competition is Kenna Chapin. The significant contributions of Kenna and her committee as well as the financial support of the Charles Pankow Foundation are gratefully acknowledged.

The Architectural Engineering Institute is one of the eight technical institutes of the American Society of Civil Engineers and is led by its Board of Governors currently consisting of Ali Memari (President); Raphael Yunk (Immediate Past President), Mark McAfee (President-Elect); Jim Ruggieri; Mark Sarkisian; Adam Hapij; and Stephanie Guy.

In the preparation of the proceedings of this conference, the contributions of Penn State AE Department staff Nancy Smith and Nancy Sabol are acknowledged. The significant contributions of Jim Rossberg (Managing Director of ASCE Engineering Programs), Adam Hapij (AEI Board of Governors member), Verna Jameson (AEI staff), and the ASCE publications department staff are also gratefully acknowledged.

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As Chair and Co-Chair of the AEI 2013 Conference, we are highly indebted to all of those mentioned above and many others not named.

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# BIM COLLABORATION IN STUDENT ARCHITECTURAL TECHNOLOGIST LEARNING

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## ABSTRACT:

This paper is the result of a qualitative case study which investigated the influence of building information modelling (BIM) collaboration on the learning of student architectural technologists based around a studio group project. The purpose of the paper is to disseminate knowledge gained into a new learning environment facilitated by the collaborative properties of a BIM application. A qualitative case study approach has been used to undertake the examination of the learners' experiences during the project. This approach allowed the author to map the complex interaction between the participants during the stages of the collaborative design project. The paper provides evidence of a new learning environment created in the studio setting. This learning is facilitated by the collaboration tools and work-set methodology of the BIM application. This case study will support higher education institutions proposing to introduce collaborative BIM applications into a built environment curriculum and also may act as a catalyst to encourage educators to adopt a similar approach to teaching in a range of other professions. This research supports a need in higher education to provide for transition from theory to workplace practice and identifies a potential for higher level learning facilitated by collaborative BIM technologies and methodologies.

**Keywords:** Architectural Technology, BIM, Building Information Modelling, Collaborative Learning, Education,

## INTRODUCTION:

There is a growing demand for closer collaboration within the built environment. This demand needs to be reflected back into the teaching and learning practices of students in the disciplines of design and construction. Penttila and Elger, (2006), suggest that diverse multidisciplinary understanding and knowledge about various factors of design and construction will be essential in the near future architectural design profile and so to provide for industry, it will be incumbent on higher education institutions to break down silos of built environment education and provide opportunities for the development of collaborative skills for students poised to enter into the design and construction industry.

A catalyst to bring about this change is the robust platform provided by building information modelling (BIM) technologies and the collaborative design opportunities it promotes. Bedrick and Rinella opt cite Bedrick-Gerber et al., (2006) suggest that building information modelling technologies and methodologies are poised to revolutionize the construction industry because of its potential to radically improve collaboration among the wide-ranging expertise needed to design and construct a building and to increase efficiency. If collaboration processes are reflected back into built environment education, a legitimate question arises as to the potential benefits for collaborative learning for the students whose discipline's fall within the design and construction industry.

Building upon a model of a constructivist learning environment proposed in a paper "Designing Constructivist Learning Environments" Jonassen (1999), this research set out to observe and record a collaborative design project taught in the Department of Architectural Technology, in the Dublin Institute of Technology (DIT). Jonassen's model design puts the emphasis on providing learning experiences that facilitate knowledge construction and in meaning making. During the collaborative design process it became apparent that a strong learning dynamic had evolved, fostered by the collaboration tools of the BIM application. Using a single exploratory case study approach, the researcher has examined the strong learning dynamic and provided evidence of a new learning environment

## REVIEW OF LITERATURE:

**Building Information Modelling (BIM).** The term building information modelling (BIM) is an extensive, wide-ranging term that covers technologies and methodologies based around the creation and co-ordination of digital building data that is visually represented in "three dimensions (3D)"on a computer screen. The subject is extensively reviewed in the *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors* by (Eastman C., Teicholz P., Sacks R., Liston K., 2008). BIM technologies and methodologies are central to integrated project delivery (IPD). The American Institute of Architects (2007, p. 1) defines IPD as "a project delivery approach that integrates people, systems, business structures, and practices into a process that collaboratively harness the talents and insights of all project participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication and construction".

BIM applications and methodologies are being increasingly taught in third level colleges across architectural, engineering, computer graphics and construction management courses see Barison and Santos, (2010) and Becerik-Gerber et al., (2011). "Over the last 5 years there has been a rapid movement from computer aided design (CAD) to building information modelling (BIM) by professional architects, engineers and construction managers and this has created several challenges and opportunities for AEC educational programmes" Becerik-Gerber et al., (2011). However, teaching BIM is not as simple as introducing the application within a module. BIM needs to be part of a holistic approach within technical design studio. Chistenson (2006) says that the successful user of Revit, in addition to understanding how the software works, must understand construction technology sufficiently well in order to intelligently define such relationships. The growing number of architectural engineering courses in AEC education is testament to a need for a professional group to have a skill-set to marry the conceptual and practical.

**Learning with BIM.** Fioravanti (2007) proposes "collaborative design as being the design method best suited to the challenges of our times". He suggests that the "fundamental components of these design problems lie in a low and selfish collaboration among actors", and to overcome this limitation he suggests that "higher education needs to deal with the lack of suitable education in cross-disciplinary collaboration and the lack of suitable ICT tools enabling collaboration to be practiced in the design of complex buildings". Denzer and Hedges (2008) investigated BIM in various classroom conditions and argue that BIM enhances group-based classroom management approaches of team learning. They use Bloom's Taxonomy, Bloom et al., (1956) as a benchmark to assess the student performance in a Design Studio Course.

They conclude that BIM allows the students to reach the evaluation level of Bloom's Taxonomy in terms of cognitive skills development, opt cite in Barison and Santos, (2010). Lonely BIM is a term used to describe isolated BIM techniques for targeted tasks, Read et al (2012). Becerik-Gerber et al., (2011) say that BIM implemented into the curricula will facilitate a multidisciplinary approach that consolidates effort and enables more efficient collaboration and can also provide a platform for exploring new team structures and collaborations and realising improved student outcomes.

**Learning spaces.** The studio has always been part of the educational experience of the student architectural technologist in DIT. The crucial difference between traditional classrooms and studios lies in the distinction between "learning about" and "learning to be" Brown (2006). The pedagogy of student-centred learning is well catered for in the open plan studio setting. Indeed this style of learning is rated highly in a paper "Designing new learning environments to support 21st century skills" Pearlman (2010). The open plan design studio is equipped with work tables on the inside allowing workspace for sketching, model-making and study.

The idea of keeping the personal computer within studio and not relegating it to a separate lab has made the integration of information communication technology into to the associated architectural technology course a smooth transition for the students. It is the replacement of the drawing board by the personal computer in the architectural technology studio as a main deliverable in terms of a learning tool, coupled with the collaborative methodologies of BIM applications that have led to the creation of a new learning environment explored within this case study.

**Cognitive Learning in the Studio.** The role of the architectural technologist / engineer is to solve technical problems within the process of delivering the architectural intent while conforming to statutory legislation. Emmitt (2002) states that "creativity still takes place in the detailed design. This is a complex process full of reasoning about constraints, exploring fixes, resolving conflicts and searching for alternatives". Jonassen (2011) states, "constraints are rarely, if ever, identified completely at the beginning of the design process, as implied by the analysis phase at the beginning of the ADDIE model, (the ADDIE model being a generic term for the five-phase instructional design model consisting of Analysis, Design, Development, Implementation, and Evaluation), rather the beliefs and constraints emerge during each cycle in the design process". Designers make decisions based on the constraints as they emerge.

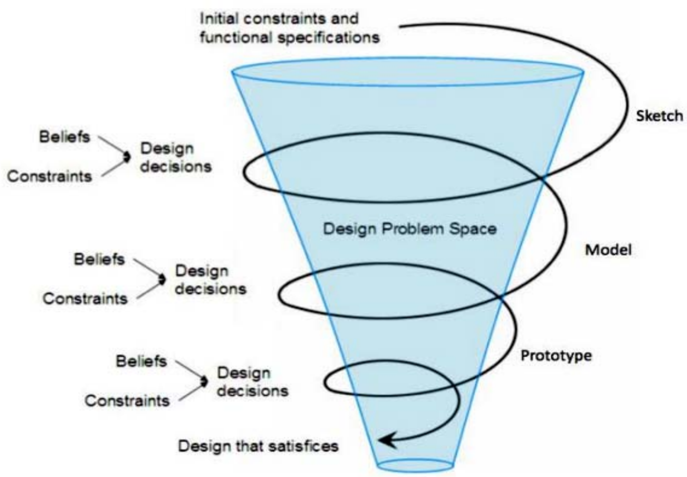


*Figure 1* Iterative Design Process Model Jonassen (2011),

This iterative design process model aligns with the decision making process the architectural technologist / engineer faces when designing a technical solution to a design problem. Emmitt (2002) suggests that "It would be easy to conclude from the design methods literature that the conceptual design stage is where the creativity takes place, ceasing at the detail design. For Emmitt (2002) this assumption would, however, be wrong as "creativity still takes place-indeed the best detailers can come up with creative solutions to very difficult technical problems-it just has to be constrained". The BIM model contributes to this iterative design process model, and can identify design problems in a way that working in 2D does not. BIM prompts students to ask questions about structures, material assemblies and detailing.

**A new learning environment for problem solving.** There has been considerable research around the creation of or what constitutes a learning environment, see for example Hannafin et al., (1999) and Wilson, (1995), "The case studio, studio team, studio group and problem based scenario are the main components of a constructivist learning environment" Ng, Fung Fai, opt cite, Barison and Santos (2010). This aligns with Jonassen (1999) who proposes a model for designing a learning environment that has four aligned components. The first component is a problem, question or project that would be the focus of the environment. This is the goal that will drive the learning process. To provide a live brief for a project would sufficiently map Jonassen's (1999) three major components in the design of the problem. The brief must have context, it should provide description of the physical, organisational and socio-cultural elements of the problem. In this case study. The real life setting is a challenge to the student and can be considered a meaningful and mindful activity where the manipulation space, in this case, the digital environment will visualise the students' argument to support their proposed solutions to the problem. In my observations of the collaborative design meetings and as outlined in this paper, it appears as though the collaborative properties of a BIM application, the studio setting, and a group project based around a live building brief, have combined to create the conditions for a new learning environment.

## RESEARCH METHODOLOGY:

The aim of this research was to explore potential benefits for learning to students through the use of collaborative learning supported by a BIM application. A qualitative case study methodology has been used to examine the learner's experiences during the project as "a hallmark of case study research is the use of multiple sources, a strategy which also enhances data credibility" Patton (1990); Yin (2003) opt cited in Baxter and Jack (2008). Potential data sources may include, but are not limited to, "documentation, archival records, interviews, physical artefacts, direct observations and participant observation" Baxter and Jack (2008). The author used six methods to capture data from the project. The student group would be working collaboratively on the digital model using a BIM application in this case Autodesk Revit.

The collaborative design process was observed by the author from start to finish over the period of 12 weeks. Unit 4 was a group of six students who chose to use a BIM methodology for their design collaboration. A dateline for formative assessment of the group work and presentation of the design proposals to the client was set by the 4$^{th}$ year head the course. The group had their first meeting with their architect in week two, the architect had received the brief the previous week. The architect had decided to take one typical building block consisting of eight senior citizens apartments on two levels with a space to the east gable end for a proposed tower block six stories high. The existing apartments are to be refurbished to meet current standards for accessibility, energy consumption and fire regulations. The case study methodology allowed the author capture information through a range of data sources including;

1. Observation of group collaborative design meetings;
2. Observation of students working in studio environment;
3. Reflective writing by the author;
4. On line blogging by the students;
5. Student's formative assessment from the project brief;
6. Project end interviews of the individual students;

Analysis of the data sets was carried out at project end. The data sets were mapped along a time line of the project and were compared, criticised and reflected upon. The data collected provided statements on the value of the new learning environment to the collaborative design process and the collaboration process on the learning of the students.

## FINDINGS:

The author took notes of his observations during the collaborative design sessions. In each of these session's the group sat around a large table in the students' studio where each member had a view of each other and were in a position to contribute verbally to the discussion. On the table were a large selection of hand sketches done in pencil and pen on light transparency paper. In the early discussions the researcher noticed that all the plans and elevations of the concept by the architect were in hard-line sketch format. The discussion was mostly initiated by the architect and covered an area of the project that required an intervention of an existing building.

The student architectural technologists contributed as "problem solvers" at this initial phase. Information contributed to the collaborative design process (CDP) blog by the students indicates that they were already taking the architects 2D sketches and making 3D massing models. The author noticed that when the architect was explaining an idea in relation to a portion of the building he used his hands to form 3D shapes and volumes to give expression the idea and to make it easier to understand and visualise. He also made use of overlays to co ordinate rooms sited directly above and below the four storey building, in effect simulating 3D. As the volume of sketches increased, problems started to occur in coordinating the information between plans, elevations and sections. Also locating sketches became difficult as the group had to shuffle through pieces of paper to locate a referred to layout.

*Figure 2,* Students first collaborative meeting

*Figure 3,* Students developing design sketches

The student group in these early sessions were also formulating technical questions as the design collaboration process continued. This had the effect of challenging their decision making skills and formulating their collaborative skills. They were also developing confidence through higher levels of involvement with the project. By the end of week four the student group were contributing as collaborators in the design process with their increased commitment to and involvement with the project

It was noticeable however that the student group were taking ownership of the project as their involvement intensified and different areas of technical design work were delegated out to individual students' by group decision. These areas of responsibility were used later to form the Revit work-sets. Work-sets are a selected collection of building elements in the BIM model. Unit four needed to work as a collaborative group, in order to make the deadline as they had five days to produce the general arrangement drawings a task that would take possibly three to four weeks working alone on a conventional 2D computer aided design application. The general arrangement drawings were handed up on time and following formative assessment by the 4$^{th}$ year studio staff unit four received the highest mark in class for their work.

The final collaborative design meeting took place on the week nine and unit four presented the BIM model projected from a personal computer on to a screen to the architect. His reaction was surprise followed by acceptance that this digital model was what he had envisioned. He also commented to the group that this was not far off from his intended design. For the rest of the meeting the BIM model was used for design visualisation references. It was observed that the architects designer instincts almost immediately came into play as he initiated a discussion related to the external material of the lower two storeys of the tower block, and how these could be altered to give a "base" to the tower. This interaction and many other subsequent design decisions were taken all prompted by the visual observation of the BIM model.

The author has reflected on the timing of introducing the BIM model into the design process and concluded that this needs to be carefully considered. The model carries a strong visual representation, perhaps too strong for the architect in the early stages of the conceptual design, in that it could unduly interfere in the architects reflective thought process.

*Figure 4,* Students introduce BIM model to architect

*Figure 5,* Detail visualisation from BIM model

## DISCUSSION:

The collaborative process involves creating a master copy of the model. This is housed on a networked server. The master copy is into divided up into work-sets. These work-sets are elements of the building for instance the external envelope, the internal walls, the stair-core, the floors, each of the students agreed to take ownership for an element and worked on this. The users synchronised with the master-copy on a regular basis. Each time a synchronizing happened all elements are updated and communicated to the group. This instant communication facilitated and prompted discussion amongst the students about the technical design proposal. The students were drawn into a conversation about the building elements and they would critically examine each other's work. Therefore, the BIM model provided enormous value in visualising the technical proposals and further enhancing the conversation. As a result of this, work was often, revised and re-visualised. The students were also teaching each other and seeing the immediate results of through the 3D visualisation of the BIM model. This was confirmed in interviews conducted with the students after the group part of the project had finished. The feedback received included the following statements:

- *Student 1 "Problem issues were much easier to see in the BIM model"*
- *Student 2 "The use of BIM works well because you are not just drawing, you are building"*
- *Student 3 "The model makes you think more of things on a macro scale"*
- *Student 4"It was a totally different way of working"*
- *Student 4"The model showed where things clashed; where you are drawing constantly in 2D you don't see these clashes"*
- *Student 5 "Working on the model has changed the way one would think"*
- *Student 1 "The model pushes you to collaborate more than one might do otherwise"*
- *Student 6 "You will see what's wrong sooner when working on a BIM model"*

The learning pyramid developed by the NTL Institute for Applied Behavioural Science ranks average retention rates against learning styles. The three highest rated learning styles on the pyramid are; discussion group, practice by doing and teach others with immediate use. The collaborative learning facilitated by BIM encompasses all three of these learning styles culminating in a new rich learning experience for the student group. This echoes Denzer and Hedges's (2008) use of Bloom's Taxonomy as a benchmark to assess the student performance confirming that BIM allows the students to reach the peak of Bloom's Taxonomy in terms of intellectual behaviour, "the evaluation level".

*Figure 6,* Proposed building visualised

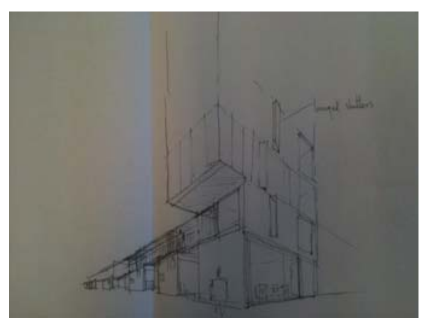

*Figure 7,* Architects early sketch proposal

From the author's observations, the work-set methodology further developed the collaborative process and contributed to a higher level of learning. For example, for a building element to interact with another from a different work-set, permission must be sought by the person wanting access to the element and permission must be granted by the owner of the work-set. This procedure facilitates a one on one conversation on how the elements will interact, resulting in a constant validation of the proposed technical design solution. The author observed continuous conversations during week seven while students were working on the BIM model and this resulted in solutions to technical design problems with deeper understanding of the technical detail as the problems were teased out by the group working in collaboration.

## CONCLUSION:

It is likely that the problems of the future, in this case building design, will have a cross-disciplinary approaches that encompass multiple areas of expertise and the ways of knowing will have to become the norm. People, in this case the stakeholders in the design and construction of buildings will need to be able to work in cross-disciplinary teams Brown (2006). The complexities of modern design and construction lead the author conclude that no one profession has all the answers to all the design questions. As new processes bring new responsibilities, the degree of specialised expertise that goes into a modern building expands constantly.

This new collaborative learning environment simulated through working with BIM has the potential to prepare and equip the student with the skill-set to be at the centre of the problem-solving collaborative process. Jonassen (2011, p. 146) also argues that although the ability to solve problems or to develop a methodology to address complex problems is something which requires practice. The creation of collaborative problem solving learning environments will address this. The fact that groups of students can collaborate together, simultaneously on a BIM model adhering to a well structured brief to propose a solution to a technical problem will give them practice that closely follows what they can expect in modern design construction workplaces.

It is the author's opinion that this structured coordinated collaborative process around the BIM model is more efficient in terms of students reaching their deadlines for project delivery and also enables a higher level of cognition, learning and understanding of technical design for buildings.

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# INTEGRATION IN THE CLASSROOM: STRUCTURAL PLANNING AND DESIGN

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**Abstract**
Structural integration in a building project involves technical, design, and communication skills. A free exchange of ideas happens when team members trust one another and when the various priorities are respected. The appreciation of collaboration methods can take years of work as a practitioner to develop. Can some of these experiences start at the university level? And by what means? Can a participatory learning opportunity be devised that will allow students to explore multiple perspectives on the same project? This paper will examine a course developed to try to answer these questions through the use of an architectural design project within a structural planning course. By beginning with an architectural concept and ending with structural analysis, students were able to see the various demands on the project. This course allowed each student to assume the 'role' of the structural engineer and architect within the same project, a daunting task for a sixteen-week course. This paper will discuss the framework, educational goals, and tools for the class. The work of the students will illustrate the various stages of the semester and their reflections will provide an insight into their struggles in an interdisciplinary learning environment. The presentation will conclude with an evaluation of the course that, for the most part, successfully engaged the students in two of the main fields in the industry and increased their appreciation of both.

**Key Words:** Architecture, Design, Education, Integration, Structural analysis

## Introduction

The integration of structure and architecture is a topic that remains current in the education of both engineers and architects. Integrating structure in a building involves technical, design, and communication skills to create better buildings and environment for us all. It is collaborative work. Ove N. Arup, the founder of the multidisciplinary engineering firm that bears his name, was an early proponent of integration and often spoke about it. For him, building was about the whole project and not just his specialized role. He summarized this as: "The term 'Total Architecture' implies that all relevant design decisions have been considered together and have been integrated into a whole by a well organised team empowered to fix priorities," (Arup, 1970). In order for true integration and collaboration to occur on a project, there must be an open dialogue among team members. A free exchange of ideas can happen when team members trust one another and respect the various priorities. In practice, trust and respect take time to develop and evolve after a team has worked together on many projects.

The question for educators is: can an experience be created at the university level to help contribute to an understanding of design and team integration? This paper details a structural planning class that creates a participatory learning opportunity devised to allow students to explore the perspectives of the structural engineer and the architect. In addition, the class asks the students to design and integrate architecture and structure. The semester-long project, the goals, the tools, and the work of the class will be illustrated to provide an insight to this 'multidisciplinary' learning environment.

**Background**

The University of Illinois at Urbana-Champaign has a long history with architecture and engineering, beginning with Nathan Clifford Ricker, the first graduate of an architecture program in the United States in 1873 and his commencing of an architectural engineering program in 1891 (Kruty, 2004). It is in this tradition that an architectural engineering curriculum remains within what is now the School of Architecture. The two year graduate program consists of approximately twenty architecture graduate students who focus on building structures, while a majority of two hundred architecture graduate students complete just a single class in structures. For the students specializing in structures, the course work at the graduate level involves nine additional courses including the course being discussed here, *Arch 556 – Advanced Structural Planning*. Within the curriculum, *Advanced Structural Planning* falls in the last semester of the second year. A survey of the students entering the course indicated that 88% are planning to practice both architecture and engineering. In terms of licensure, 34.4 % intend to pursue only the professional license in architecture and 65.6 % said they would seek out both and architecture and engineering licenses.

**Educational Goals and Framework**

As a culminating graduate level course, the course looks to apply higher level educational objectives. The course seeks to expand the students' knowledge of loads on buildings, how to create a structural system for a building, structural integration, and the work process of a structural engineer. Most students, prior to entering this course, have significant experience in architecture and structural member design, but not experience in putting them together. The course encourages students to look at building holistically. The educational goals of the course are summarized in Table 1. The course has been designed to create a learning environment that is "…increasingly facilitated by exploration, interaction, and problem-solving…" (CAUDIT, 2010). The advantage of this format is that it provides situations for the student where no single answer is expected. Consequently, it appeals to this generation of students who are seeking a more interactive education. The first time the class format was taught (Spring 2011) required that students find an architectural and structural solution for a long-span indoor practice football stadium. In the second (Spring 2012), the students participated in the American Collegiate Schools of Architecture/American Institute of Steel Construction Student Design Competition (ACSA/AISC) and designed a building for a Culinary Arts College. The Culinary Arts College building program included restaurants, classrooms, and a space that used a long-span structure. The semester project is broken into three stages: Concept Design, Schematic Design I, and Schematic Design II.

| | Building Loads | Structure | Integration | Architectural Discipline | Structural Engineering Discipline |
|---|---|---|---|---|---|
| **Knowledge** | | | | | |
| **Comprehension** | | | Summarize various ideas on the topic | | Grasp context in which engineering is completed |
| **Application** | Derive Loads for Project | | Experiment with architecture and structure | | Apply work methods and tools |
| **Analysis** | Analyze members based on load cases | Order vertical and horizontal structural systems | Identify areas of potential conflict | Explain delivery methods and tools | Divide project into distinct portions & order work |
| **Synthesis** | Modify loads as construction and form refined | Predict sizes and behavior of members and systems. Modify as needed. | Create solution to solve two priorities | Compose project design | Iterative structural design |
| **Evaluation** | Evaluate construction and form based on loads | Compare solutions and explain choices | Evaluate options and decisions | Evaluate design decisions | Evaluate design decisions |

Table 1: Learning Objectives for the Class

**Phase 1 – Concept Design**

To start the project, the students were given a project brief that listed building type, building site, and architectural requirements. For example, the NCAA field and the supplementary program were provided for the Indoor Practice Stadium project. Four weeks were scheduled for the students to develop their concept design and much of this work was completed independently. This phase allowed students an opportunity and freedom to use both their architectural and structural training in the most creative stage of the project. The objectives for this stage are summarized in Table 2.

The requirements for this phase included models, presentation boards, and a presentation to a jury. Students used programs such as Rhino, Sketch-up, Revit, and AutoCAD to develop and articulate their project from overall massing to interior renderings. Reviews provided an opportunity to test the validity of the projects and to receive feedback. For many students, the experience was challenging. Comments from the architectural professors centered on the architectural design of the structure and questioned if the structure was being used in the correct manner. The students were asked to examine their preconceived notions of architecture and structure simultaneously and this presented a new phenomenon for them.

| | **Building Loads** | **Structure** | **Integration** | **Architectural Discipline** | **Structural Engineering Discipline** |
|---|---|---|---|---|---|
| **Knowledge** | Introduction to loads and combinations | | Reading of integration texts | | |
| **Comprehension** | Load determination through ASCE 07-10 | Describe types of floor support systems | Students interpret ideas of integration | | Readings from structural engineers |
| **Application** | Practice Problems for load determination | Illustrate strengths of floor systems in presentation | Case studies presented by students evaluating integration | Weekly presentation of ideas | |
| **Analysis** | | | | Initial design concept | |
| **Synthesis** | | | | Further refining of project | |
| **Evaluation** | | | | Jury Review of project | |

Table 2: Phase 1—Concept Design Objectives

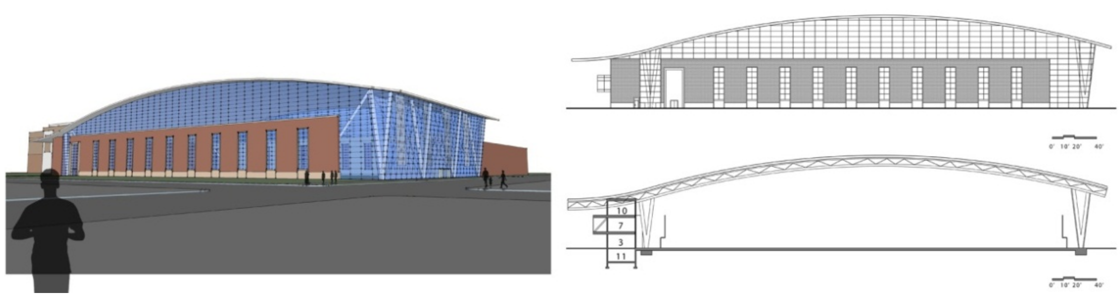

Figure 1. B. Lyons, R. Marshall, & B. Westergaard. Concept for the Indoor Practice Stadium.

The student's work illustrated some of this duality and the exploration that occurred. Their projects can be seen to be very schematic in their articulation. In Figure 1, an example from the Indoor Football Stadium project, there is a long span roof supported by a of truss system. The truss is sketched out in the section, but the roof system, portrayed elsewhere, shows almost no thickness. It can be seen that the students have not yet put the two ideas of structure and architecture together, intellectually or literally. Also, in the overall rendering of the building, there is a large laterally unsupported masonry wall. This project addressed many of the architectural requirements—site placement, massing, entrance, and started to articulate the structure both vertically and horizontally. It was a good beginning and it had many areas on which to solidify in the next phases.

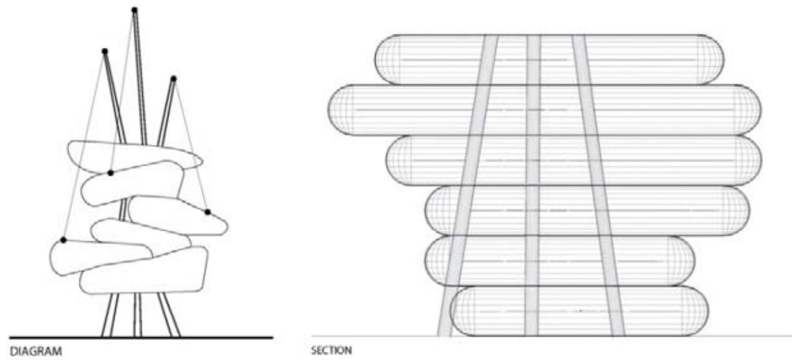


Figure 2. J. Johnson & N. Pall. Concept design for the Culinary Arts College.

The project shown in Figure 2 was one team's design for the Culinary Arts College and the diagram illustrates a really rough, but ambitious project. It includes vertical supports in the form of columns and hangers, and little else structurally. The section, cut through a more formalized version of the building, shows much of the same. The depiction of the floors and roofs as thin lines reveal that no structure has been conceived. As in the first project, there are areas that were questioned, but the excitement about the ideas can be seen. In both projects, the structure was far from a whole system. The architecture and the structure needed more development and unification in these projects.

**Phase 2 – Schematic Design I**

| | **Building Loads** | **Structure** | **Integration** | **Architectural Discipline** | **Structural Engineering Discipline** |
|---|---|---|---|---|---|
| **Knowledge** | | | | | |
| **Comprehension** | | | | | Introduce tools & project-based work methods |
| **Application** | Derive loads for own project | | | | Illustrating ideas through presentations |
| **Analysis** | | Order vertical and horizontal structural systems | Connect structural system to architectural system | | |
| **Synthesis** | | Predict sizes and behavior of members and systems | | | |
| **Evaluation** | | | | | |

Table 3: Phase 2—Schematic Design I Objectives

In the second phase of the project, the concentration moved from mostly architectural to mostly structural. The students began to incorporate comments received from the reviews. The teams started to construct a structural system and determined the loads for their building. The objectives for this stage are summarized in Table 3. In the Indoor Practice Stadium project, this meant understanding the primary, the secondary, and the span of the structural systems. The components of the main system were then diagrammed. For the Culinary Arts College, the floor system was chosen, the column grid was laid out, and the long span support configured. This portion of the work was three weeks long. During this time, the teams presented their work twice to their classmates for evaluation and discussion. In this phase, the students were asked to move beyond structural element design and to start to visualize the whole system. The students were synthesizing the structural elements into a system and integrating them into their architecture.  The requirements for this phase included drawings such as plans and sections, as well as a load calculation package based on ASCE 07-10. Students used traditional tools to find preliminary sizes such as using rules of thumb and design guides like the AISC Steel Manual, or ICC-ES Evaluation Reports.

In Figure 3, the conception of the main structure for the Indoor Practice Stadium is shown. It had three-dimensional trusses that repeated at regular intervals to form the primary roof support system. A secondary system emerged to support the roof decking. The members for both systems were dimensioned and started to show depth or thickness.

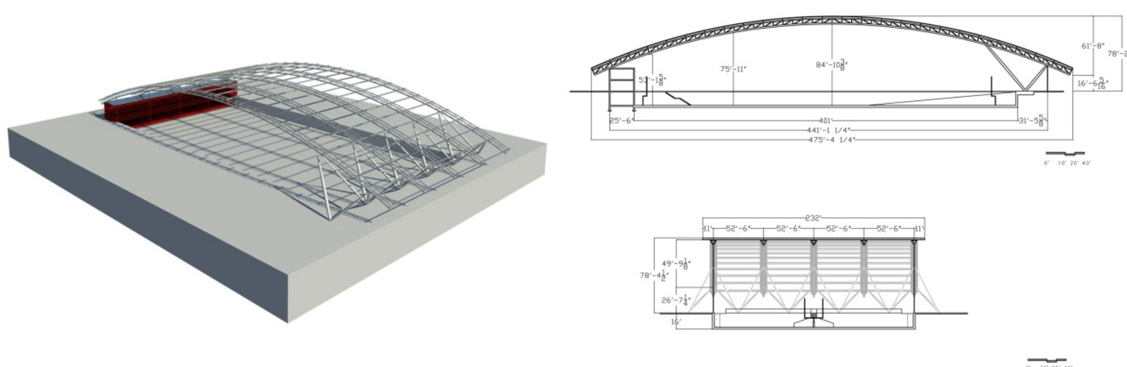


Figure 3.  B. Lyons, R. Marshall, & B. Westergaard. Structure for the Indoor Practice Stadium.

The Culinary Arts College, in Figure 4, changed from amorphous shaped structures to rectangular ones, though the stacking remained. The double layer of roof/floor was removed at intersection of the two. A center core was added to aid the building's stability. The horizontal and vertical systems became plates constructed of planar trusses. A detail of how the trusses will connect was envisioned. Of these two projects, the second one had the more dramatic change. The round corners have become square and where there was no structure, now it is all structure. The first project demonstrates a more subtle change. The form remains similar, but the system started to populate and became richer. In this stage, the students assembled the structure and determined the loads to be supported. The next step was to understand how it all works together.

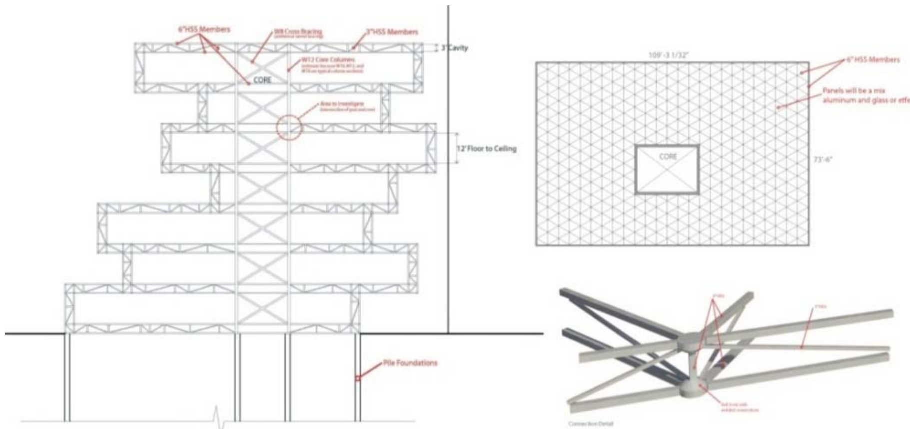

Figure 4. J. Johnson & N. Pall. Structural development for the Culinary Arts College.

## Phase 3 – Schematic Design II

| | Building Loads | Structure | Integration | Architectural Discipline | Structural Engineering Discipline |
|---|---|---|---|---|---|
| **Knowledge** | | | | | |
| **Comprehension** | | | | | |
| **Application** | | | | | Apply work methods and tools |
| **Analysis** | Analyze members based on load cases | Perform analysis using structural software | Identify areas of potential conflict between sizes and location and architectural requirements | | Divide project into distinct portions & order work to determine analysis components |
| **Synthesis** | Modify loads as construction and form are refined | Modify members sizes as needed by performance | Create solution for structure and architecture | Bring together structural and architecture. Modify design as needed. | Iterative structural design for members and systems. Weekly presentations. |
| **Evaluation** | Evaluate construction and form based on loads | Evaluate and refine structure. Verify performance of structural model. | Access decisions that were made, determine if new solution is needed. | Evaluate design decisions, refine as needed. Bring project together cohesively. | Evaluate design decisions and bring project together cohesively. Evaluations by Engineers |

Table 4: Phase 2—Schematic Design II Objectives

The final phase brought the architectural and structural components of the project together. However, before this could be completed, the students spent a good amount of time analyzing the building structure. The tools used in this phase of the project varied and increased in number. Adding to the previous tools, the students used structural analysis software including RISA, RAM, and SAP. The challenge with using the software analysis packages included a lack of familiarity and understanding distinct design packages. The students' first instinct was to examine the building as one large structural model that they often could not understand. To assist with this, design modules were derived: floor systems and beam design, column take-downs and column analysis, cantilever or long span system determination, and modeling of the lateral system.

This phase involved iterative engineering design. Students started with the sizes and composition that they had estimated in the previous phase. As one might expect, not everything worked. The students then had to determine why this was and how it could be improved. Students had to understand their structure and how it performed for the strength, deflection, and stability requirements. Then, the teams were in the position where they had to integrate the structure before the architecture or the structure could move forward. Under these circumstances, they re-designed the structure or the architecture. Students negotiated through the requirements.

Much of the class time during this last phase was used as work sessions. Teams presented their work and the challenges they faced were aired. Toward the end of the semester, the student projects were reviewed by practicing structural engineers. The students needed to convey both the architectural and structural goals to the reviewers in order to elicit comments that would aid their project. They found the discussions useful and it was enlightening for them to see the analytical skills of another profession.

At the end of the semester, a complete project package was due. This included: students' personal journals, structural drawings (floor plans, column schedule, and truss elevations), digital structural models, and a calculation binder. The teams also created presentation boards to summarize their project. Specific objectives for the phase are summarized in Table 4.

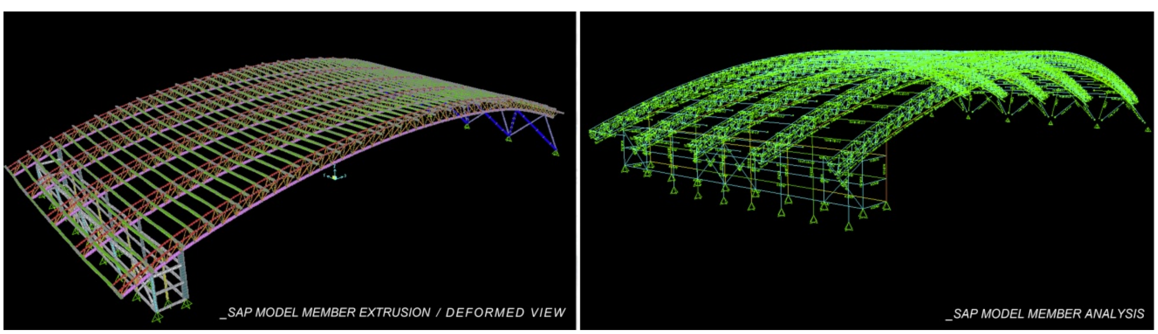

Figure 5. B. Lyons, R. Marshall, & B. Westergaard. Structural Analysis on Roof Trusses.

The SAP model shown in Figure 5 illustrates the work on the trusses in the final phase for the Indoor Practice Stadium Project. The long span elements needed to withstand the ASCE load cases and perform well under deflection. During this stage, the system went through an evolution. The team had originally wanted a composite concrete metal deck construction for the roof, but after analyzing the structure, it was changed to a lighter system to reduce the loads. The team also had to increase member sizes in order for the system to work, but in the end, the team was happy with the overall results.

After investigating a planar truss system, the team working on the Culinary Arts College understood the system that they had devised provided some difficulty. It was complicated and modeling it proved no help in this. The computer model was too large and the team was not able to come to any intuitive understanding of how it worked. The team was also concerned about the construction challenges of the many members coming into the same joint. The structural engineers' review confirmed the students' fears. The team then found a solution using a steel grillage for the horizontal system and large scale trusses for the vertical one. The new system and the proposed detailing can be seen in Figure 6. While the structure and the architecture changed significantly from the original sketch, the team was able to create a workable solution that they believed met their original intent.


Figure 6. J. Johnson & N. Pall. Final Presentation for the Culinary Arts College.

**Concluding Reflections**

In the second teaching of this class, the students were asked to participate in the *Illinois Initiative on Transparency in Teaching and Learning in Higher Education.* This national study evaluates using transparent teaching methods with students. The class format naturally included transparency with such items as students having open and regular feedback on their work. At the end of the course, students were asked to answer a series of questions about their learning experience and 87% of the students responded. The course received very positive feedback with 75% percent of the responders stating that they learned to connect information from a variety of sources and that it made them more confident about succeeding in their field (IITTLHE, 2012). Two questions spoke to the subject of integration. When asked if the course helped them with learn to collaborate effectively with others, 85% of the responders said it did, with 77% said that it helped 'a lot' or 'a great deal.' When asked if they were likely to apply what they learned in the class in contexts outside of the field, 92% said that they were 'very' or 'extremely likely to do so' (IITTLHE, 2012). Both of these results validate the course objectives and the exposure to different points of view on the same building.

While no course is perfect, these classes had some very positive results. The entering students had completed several iterations of the architectural design process. On the structural side, they understood structural analysis methods and knew deflection equations. However, they had not approached a structural system in this detail. A project was constructed as to give students the ability to investigate integration and a building's structural system simultaneously. Determining and applying the loads to their building, students were able to see the load where structure was needed. Students used structural analysis software and saw the complexity of both creating and loading structural models. They experienced the time it took to modify these same models with architectural or structural changes. Their journals were filled with discussions of the software, models, and changes that they were making. Students saw that there was no one correct system, but a series of choices that impacted other decisions. By the end of the process, the class had a much larger appreciation for the work of the structural engineer.

The other thing that the course did was get students to think more broadly about the relationship between architecture and structure. Because of the reviews, the working and reworking of the project, and exposure to integration, the connection between the two fields was made clearer. This can be seen in the reflections of one student:

> This semester has opened my eyes to how important it is for architects to work together from the beginning with engineers to have a thorough and well thought out design. I find that structure is just as import and as architecture and can be a vital design tool. Whether a complicated design solution or simple design solution, structure can allow for new and various program solutions, it can also serve as a main design for an architectural concept (Student Journal, 2012).

For those seeking architectural and structural integration, whether practitioner or professor, one could not ask for more.

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# ENTREPRENEURIAL CHARACTERISTICS OF ARCHITECTURE AND BUILDING STUDENTS IN NIGERIA: A CASE OF COVENANT UNIVERSITY

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Abstract

The Nigerian government has a mandate to create five million jobs annually within the next three years and establish more skills acquisition centres. Although, the existing universities in Nigeria can influence the development of entrepreneurial skills, entrepreneurship had been considered a subject mainly for students with predominantly business background. Nowadays, entrepreneurship is gaining much ground even among other disciplines with a non- business background. The aim of this research is to compare the entrepreneurial characteristics of architecture and building students of Covenant University. A sample of 115 Covenant University students comprising of 59 architecture students and 56 Building students responded to a 10-item questionnaire. Data was analyzed using Mann-Whitney test. The findings revealed that there is no statistically significant difference between the entrepreneurial characteristics of creativity, self confidence/awareness, risk - taking propensity and need for achievement of architecture and building students. A different finding was however revealed under the entrepreneurial characteristic of market knowledge. Although Covenant University is already empowering all its graduates entrepreneurially to contribute significantly to the socio-economic development of the country, other educators should incorporate into their curriculum elements that enhance the development of entrepreneurial characteristics because it is imperative for self employment and employment career path.

Keywords: Architecture, Building, Covenant University, Entrepreneurial Characteristics, Students.

## INTRODUCTION

### Background

Entrepreneurship has no universally accepted definition. It is however, presently associated with innovation and new venture creation (Nabi et al., 2006; Kuip and Verheul, 2003). Entrepreneurship can also be present within existing organizations and even outside the business environment. In such situations it is referred to as intrapreneurship (Edwards et al, 2009).

In recent years, the importance of entrepreneurship has been widely acknowledged. It plays a more vital role in developing countries because it creates jobs, increases productivity, spurs innovation and grows the economy (Ogundele, 2007; Omeje, 2008).

The Nigerian government has among other mandates to create five million jobs annually within the next three years, establish more skills acquisition centers and implement the local content policy in all sectors, in order to boost job creation in the country.

The existing educational system in Nigeria can influence the development of entrepreneurial skills. This is because the academic context is an important environment that impact's on an individual's entrepreneurial tendencies (Franke and Luthje, 2004). Moreover, the educational system creates awareness of alternative career choices and broadens the horizon of individuals, equipping them with cognitive tools and enabling them to perceive and develop entrepreneurial opportunities (Kuip and Verheul, 2003).

However, in times past entrepreneurship was considered a subject for students with a predominantly business background more than any other. Nowadays, the subject of entrepreneurship is gaining much ground even among other disciplines with non- business background (Edwards et al., 2009). This is because all students have and can develop a set of skills that can make them suitable for creating jobs for themselves and others.

Furthermore, the knowledge of entrepreneurship fosters the development of business skills, creativity and self confidence (Oroka et al., 2008) which are highly sought by existing private and public organizations (Binks, et al., 2006).

**Architecture and Building students of Covenant University**

Covenant University offers several degree programs at the undergraduate level including Architecture and Building. The University has a custom – built program called Entrepreneurship Development Studies (EDS) which is an all semester program and is compulsory for all students of the university irrespective of the students chosen field of study.

The operations of the EDS is housed in the centre for Entrepreneurial Development Studies (CEDS) and the vision of the centre is to empower Covenant University graduates entrepreneurially so that they can contribute significantly to the socio-economic development of Nigeria.

The foregoing has necessitated a desire to conduct a research with the aim of comparing the entrepreneurial characteristics of Covenant University students in the Architecture and Building programs. It also seeks to analyze the hypothesis H0: There is no statistically significant difference between the entrepreneurial characteristics of Architecture and Building students of Covenant University.

# THEORETICAL FRAMEWORK

**Theories of Entrepreneurship**

Cunningham and Lischeron (1991) identified six major schools of thought on entrepreneurship namely: the great person school, the psychological characteristics school, the classical school, the management school, the leadership school and the intrapreneurship school. Proponents of the great person school (Schumpeter 1934; Schultz 1975) are of the opinion that entrepreneurs are born and not made. They believe that entrepreneurs possess certain characteristics such as energy and persistence that differentiate them from non-entrepreneurs. In the psychological characteristics school, proponents like (Gartner 1989) view entrepreneurs as individuals who possess unique values, attitudes and needs, which drive them. This thought also encompasses the theories of entrepreneurial events (Shapero and Sokol 1982) and planned behavior (Ajzen 1991). The entrepreneurial events theory is based on the fact that entrepreneurial intention is influenced by certain situational context like personal characteristics, perceptions, beliefs, values, background and environment. While the theory of planned behavior is based on the belief that actions are preceded by conscious decisions to act in a certain way (Ajzen 1991). Proponents of the classical school such as (Drucker 1985) believe that innovation is the central theme of entrepreneurship. The management school opines that entrepreneurs are persons who organize, own, manage and assume the risk of an economic venture (Cunningham and Lischeron 1991). The leadership school posits that entrepreneurs are leaders who are able to adapt their style to the needs of people (Cunningham and Lischeron 1991). Proponents of the intrapreneurship school (Timmons 1999; Carrier 1996) believe that entrepreneurial skills can be useful in various organizations through the development of independent units to create market and expand services.

**Entrepreneurial Characteristics**

Entrepreneurial characteristics is a term used to describe the profile of an entrepreneurial individual (Kuip and Verheul, 2003) .Several entrepreneurial characteristics have been identified in the literature. However, for brevity this study looks at only the following entrepreneurial characteristics:

1. **The need for achievement -** is the tendency to set challenging goals and strive after these goals through own effort (Caird 1992)
2. **Risk-taking propensity** - is exposing oneself to loss or disadvantage (Kuip and Verheul (2003)
3. **Creativity** - is developing new methods instead of using standard procedures (DeBono, 1992)
4. **Self awareness** - is the degree of realism in the estimate of an individual's own abilities enhancing an adequate response to the environment (Lawler, 1973)
5. **Market knowledge** - is the knowledge of rules, conditions, opportunities and challenges surrounding a business. (Aghazanmani and Roozikhah, 2010).

## Entrepreneurship in Nigerian building, construction and architecture

According to Bala(2011) entrepreneurship in Nigerian building construction and architecture can be classified into the following categories: building design entrepreneurship, building preliminaries entrepreneurship, building sub-structures entrepreneurship, building super structures entrepreneurship, building roof work entrepreneurship, building services entrepreneurship, building finishing entrepreneurship and building external work entrepreneurship.

Most of the entrepreneurs in the Nigerian construction industry belong to the small and medium size category (Adams, 1997). Although contractors among these entrepreneurs in the Nigerian construction industry far out number the number of foreign contractors (Aniekwu, 1995), the annual volume of work done by the foreign contractors is more.

Entrepreneurs in the Nigerian construction industry are unable to compete with foreign firms because of the latter's superior human, material and financial resources (Adams, 1997; Ogbebor, 2002; Chen, Chiu, Orr and Goldstein, 2007).

## METHODOLOGY

The methodology adopted for this research is quantitative. The study utilized a descriptive research design. The sample was made up of 115 Covenant University students from architecture and building programs comprising of 59 architecture students and 56 Building students. Data were gathered in June, 2012 using a set of questionnaire to assess the entrepreneurial characteristics of the students. The questionnaire was developed based on the modification of a previous instrument by Aghazamani and Roozikhah (2010).

The reliability of the constructs has a Cronbach α value of 0.72. The measurement of items in the survey questionnaire was based on a 5 point Likert scale with 1 representing "strongly disagree" and 5 representing "strongly agree". The collected data were analyzed using the IBM SPSS statistics.

In order to give insights into the practice of entrepreneurship in the Nigerian construction industry, a case study is presented.

Table 1 illustrates the 10-item close- ended questionnaire that was used in this study.

Table 1: Questionnaire employed adapted from Aghazamani and Roozikhah (2010)

| Question | SD | D | UD | A | SA |
|---|---|---|---|---|---|
| **Market Knowledge** | | | | | |
| Q1. I know much about rules, conditions, opportunities and challenges for establishing and running a business | | | | | |
| Q2. I have visited a factory (and) or worked in an office while pursuing my education | | | | | |
| **Need for achievement** | | | | | |
| Q3. I am interested in taking long – term courses to learn more about job markets | | | | | |
| Q4. I would be satisfied with continuous employment and payment by fixed salary | | | | | |
| **Risk-taking propensity** | | | | | |
| Q5. I prefer a job involving change, travel and variety even though the job is less secure | | | | | |
| Q6. I prefer to run my own business rather than participate in a lower-risk business after graduation | | | | | |
| **Self confidence/awareness** | | | | | |
| Q7. I am happy with my life and talents | | | | | |
| Q8. I have the ability to cope with challenges in the job market | | | | | |
| **Creativity** | | | | | |
| Q9. I enjoy proposing new solutions to current challenges | | | | | |
| Q10. I enjoy offering creative ideas to challenges | | | | | |

## Case study

The company studied is a contracting company that was founded over twenty years ago. It has 5 people in its employment as permanent staff and over 20 people as contract staff. It annual turn over is between a hundred and two hundred million naira.

The company provides a comprehensive construction service covering the full spectrum of building works for public and private clients.

Since interest rates from the banks are very high, the company depends on mobilization fee from projects and other internally generated funds to stay afloat. It also renders other ancillary services such as Quantity Surveying, Project Management and Hospitality business.

The company has participated in a joint venture with an American firm.

Major challenges faced in the construction business are: difficulty in accessing funds, lack of standardization on the construction industry and non-regulation of the construction business.

## Data Analysis

The hypothesis was tested using the Mann – Whitney test with a confidence level of 95% (0.05). Mann-Whitney test is a recognized non-parametric test for assessing two independent samples. This test has also been employed recently (Aghazamani and Roozikhah, 2010) to examine the entrepreneurial characteristics of Iranian and Swedish University students.

## Results

The results from table 2 indicate that the Mann-Whitney test results for the constructs of creativity, self confidence/awareness, risk taking propensity and need for achievement are all □ 0.05. This certainly provides sufficient information to accept the null Hypothesis and to declare that there is no statistically significant difference between the entrepreneurial characteristics (for the above mentioned constructs) of architecture and building students of Covenant University.
However, the Mann-Whitney test result for the construct of market knowledge reveal that the p value for students that have visited a factory or worked in an office while in school is 0.016 which is □ 0.05. This suggests that there is a statistically significant difference between Architecture and Building students that have visited a factory or worked in an office while in school. The p value for Architecture and Building students who are knowledgeable about the rule and conditions for establishing a business is 0.203 which is □ 0.05 indicating that there is no statistically significant difference between Architecture and Building students who are knowledgeable about the rule and conditions for establishing a business.

Table 2: Frequency of results based on each question on Mann – Whitney Test

| **Question** | **Program** | **N** | **Mean rank** | **Sum of rank** | **P- value** | **Decision** |
|---|---|---|---|---|---|---|
| **Market Knowledge** | | | | | | |
| **Q1**. I know much about rules, | Arch | 59 | 54.34 | 3206.00 | 0.203 | Accept null hypothesis |
| conditions, opportunities and | Bldg | 56 | 61.86 | 3464.00 | | |
| challenges about establishing | **Total** | **115** | | | | |
| and running a business | | | | | | |
| **Q2**. I have visited a factory | Arch | 59 | 64.94 | 3831.50 | 0.016 | Reject null hypothesis |
| (and) or worked in an office | Bldg | 56 | 50.69 | 2838.50 | | |
| While pursuing my education | **Total** | **115** | | | | |
| **Need for achievement** | | | | | | |
| **Q3**. I am interested in taking | Arch | 59 | 55.58 | 3279.50 | 0.411 | Accept null hypothesis |
| long – term courses to learn | Bldg | 56 | 60.54 | 3390.50 | | |
| More about job markets | **Total** | **115** | | | | |
| **Q4**. I would be satisfied with | Arch | 59 | 59.12 | 3488.00 | 0.704 | Accept null hypothesis |
| continuous employment and | Bldg | 56 | 56.82 | 3182.00 | | |
| Payment by fixed salary | **Total** | **115** | | | | |
| **Risk-taking propensity** | | | | | | |
| **Q5**. I prefer a job Involving | Arch | 59 | 55.19 | 3256.00 | 0.336 | Accept null hypothesis |
| change, travel and variety | Bldg | 56 | 60.96 | 3414.00 | | |
| Even though the job | **Total** | **115** | | | | |
| is less secure | | | | | | |
| **Q6**. I prefer to run my own | Arch | 59 | 58.69 | 3462.50 | 0.808 | Accept null hypothesis |
| business rather than participate | Bldg | 56 | 57.28 | 3207.50 | | |

| | | | | | | |
|---|---|---|---|---|---|---|
| In a lower-risk business after graduation | **Total** | **115** | | | | |
| **Self confidence/Awareness** | | | | | | |
| **Q7.** I am happy with my life and talents | Arch | 59 | 62.23 | 3671.50 | 0.120 | Accept null hypothesis |
| | Bldg | 56 | 53.54 | 2998.50 | | |
| | **Total** | **115** | | | | |
| **Q8.** I have the ability to Cope with challenges in the job Market | Arch | 59 | 61.07 | 3603.00 | 0.284 | Accept null hypothesis |
| | Bldg | 56 | 54.77 | 3067.00 | | |
| | **Total** | **115** | | | | |
| **Creativity** | | | | | | |
| **Q9**. I enjoy proposing new solutions to current challenges | Arch | 59 | 56.64 | 3342.00 | 0.626 | Accept null hypothesis |
| | Bldg | 56 | 59.43 | 3328.00 | | |
| | **Total** | **115** | | | | |
| **Q10**. I enjoy offering creative ideas to challenges | Arch | 59 | 57.03 | 3365.00 | 0.722 | Accept null hypothesis |
| | Bldg | 56 | 59.02 | 3305.00 | | |
| | **Total** | **115** | | | | |

## Discussions

The aim of this research is to compare the entrepreneurial characteristics of Covenant University students in the Architecture and Building programs and to test for the hypothesis H0: There is no statistically significant difference between the entrepreneurial characteristics of Architecture and Building students of Covenant University.

Most of the students who participated in the study have positive entrepreneurship intentions for the future. This may be because Covenant University motivates its students towards entrepreneurship by providing all semester entrepreneurship courses for all its students irrespective of the students chosen field of study. This finding is consistent with the findings of Peterman and Kennedy (2003); Lee et al., (2005); Souitaris, Zerbinati and Al- Laham (2007) and Cho (1998) who found that exposure to entrepreneurship education increases entrepreneurial intention.

The findings also revealed that there is no statistical significant difference between the entrepreneurial characteristics of creativity, self confidence/awareness, risk - taking propensity and need for achievement among Architecture and Building students of Covenant University. However, there is a significant difference between Architecture and Building students that have visited a factory or worked in an office while in school. This may be because most of the students that filled the questionnaire from Architecture were in the final year and must have gone through the student industrial work experience (SIWES) program in the preceding year. Consequently, the number of architecture students that have worked in an office while in school is significantly greater than building students who have worked in an office while in school.

Overall there is no statistically significant difference between the entrepreneurial characteristics of Architecture and Building students of Covenant University.

## CONCLUSION

Architecture and Building students of Covenant University possess similar entrepreneurial characteristics. Moreover, they have positive entrepreneurship intentions for the future. It is suggested that policy makers especially in universities should incorporate elements that enhance the development of entrepreneurial characteristics. From the challenges harvested from the case study government should also provide legal and institutional frameworks that would enable entrepreneurs gain access to funds.

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# ASSESSING THE IMPACT OF USING PHOTOGRAPHIC IMAGES TO INFLUENCE BUILDING RETROFIT DESIGN EDUCATION

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## ABSTRACT

This research examines the benefits and challenges associated with largely self-guided learning as a method for encouraging students to deepen their understanding of sustainable building design principles. This work builds off of prior work related to this topic in which first-year architectural engineering students were tasked with redesigning an existing curtain wall design to make the building perform more sustainably. In this follow-up research, students were given a list of several possible building materials to be used on a curtain wall design and several photographs of the existing building with the curtain wall digitally removed and also with it faded in the images so that students could document their ideas on the photos in the context of the surrounding built space. Pre-tests and post-tests, reflection questions, and focus group assessments were used to better understand the implications of this activity. It was found that, while students' understanding of sustainable building topics was not significantly enhanced from this activity, they did show improvement in the design processes that were employed as compared to the prior work where the additional materials and provided photographs were not included. The students who participated in this activity experimented with creating more design iterations as compared to prior students who were not given the images and material list to guide their decisions. The designs submitted by students during this activity were also more focused on the building element in question and did not deviate to other building elements as often. The findings from this work will serve as a point of comparison for future efforts related to better understanding the educational value of augmented reality technology in improving sustainable design skills in first year engineering students.

*Keywords*: Engineering education, situated learning, sustainability

## INTRODUCTION

In the engineering discipline, students develop knowledge of fundamental engineering principles so that they may eventually apply that knowledge after graduation (Johri and Olds, 2011). During the early years of engineering students' education, many of the courses in the curriculum are focused on helping students develop the necessary prerequisite skills for future engineering-specific courses. These prerequisite courses, including calculus, physics, chemistry, are important in preparing students to take later discipline-specific courses, but they do not necessarily put students in a position to engage with discipline-specific activities. As suggested in Ohland et al. (2008), students in higher education, including, the engineering disciplines, tend to disengage with the major courses throughout their academic career. This work attempts to create a learning environment where students can engage with discipline-specific course content in a way not afforded through traditional methods.

A design activity was presented to first-year engineering students that challenged them with designing a new curtain wall for an existing building on Penn State's campus to attempt to make the facility perform more sustainably. The School of Architecture and Landscape Architecture's (SALA) Stuckeman Family building is, at the time of this paper's composition, tied for the highest LEED® rated building on Penn State's campus with its gold rating (See www.usgbc.org for more information on LEED). This facility, shown in Figure 1, has many design elements that aim to make it perform more sustainably than traditional building designs. Students were given tours of this facility to better understand some of these sustainable design elements. This background understanding of this building that students developed through tours made it an ideal setting for the implemented design activity.


**Figure 1: The School of Architecture and Landscape Architecture's (SALA) Stuckeman Family Building located on Penn State's University Park campus can be seen with its curtain wall from the interior and exterior perspectives.**

## Background

Situated learning theorists argue that the best way for a student to learn new content is through applying that content in the context in which it will eventually be used (Lave and Wenger, 1991; Hung, 1999). This type of learning-through-doing strategy has also been more recently called for by Litzinger et al. (2011) who suggest that broad changes to curricula are required to better prepare engineering students for their future careers. This particular research project takes an exploratory step toward these broad goals through the addition of a building design project incorporated into the first-year seminar experience.

One of the key challenges associated with a learning-through-doing approach with building design by first-year engineers is that the students have not yet had a great deal of background experience related to the task at hand. This lack of training requires students to gather information on their own during the activity so that they may generate plausible building designs when the class session is over. The concept of self-education has both supporters and detractors in the educational research realm who identify both advantages and disadvantages with this type of learning (Katyal and Evers, 2005; Brydges et al., 2010). Self-education can offer benefits to students by forcing them to learn how to learn, which can help develop skills necessary for lifelong learning (Brydges et al., 2010). The knowledge obtained through self-education also tends to be perceived as more applicable to real life by the students and therefore motivates students to learn for the purposes of education, as opposed to motivation to perform well on exams (Katyal and Evers, 2005). Critics of self-learning argue that there is the possibility that students will develop bad habits or misinterpret content in the process of learning (Brydges et al., 2010). This work explores this method of education to identify specific benefits and challenges related to situated learning in the building design context.

## APPROACH / METHOD

The research presented in this paper extends prior work that has been completed to better understand the benefits of open-ended design education for first-year engineering students (Ayer et al., 2012). The prior work tasked students with designing a new curtain wall for an existing building on Penn State's campus to make it perform more sustainably. In this prior implementation, students were not provided with any suggestion of how to complete the design process or how to document their ideas. Students were provided with a similar level of background instruction related to sustainability and the design process. Students were responsible for determining for themselves how they should best approach the design challenge within a 50 minute class session. The students generally explored the existing design and attempted to tweak the existing design. A few students developed designs that incorporated different building materials than those used on the existing facility, but this was not the norm. Additionally, several students deviated from the curtain wall design problem to attempt to change other aspects of the building's design during their work. This prior work helps to serve as a control group with which to compare the findings of this paper's research.

### Assignment

The work presented in this paper offered students a similar experience to the prior implementation of this design activity, requiring them to generate a new curtain wall design for an existing building to make it perform more sustainably, but this implementation also gave students a few additional resources to use to help them complete the design challenge. In this second implementation, students were given images of a typical curtain wall bay in the existing building with the existing curtain wall dimmed and also with the current design removed entirely. These can be seen in Figure 2.

**Figure 2: Two printed images were provided to students completing the design activity on which to illustrate their design ideas.**

In addition to the printed images supplied to the students, they were also given a list of possible building materials that they could use on the project. The list included a wide range of materials that could be used in a building project, including concrete, brick, copper, drywall, stone, stucco, wood, or architectural glazing choices. Students could select as many of the materials listed as they felt they wanted. To further encourage students to think creatively and challenge the choices that were chosen on the existing design, students were also told that they could deviate from the provided list of materials if they felt there was a better material choice that could be used in their design.

**Students' prior knowledge**

Prior to the design activity class session, students were presented with a 50 minute lecture related to building sustainability and the LEED® point rating system. This lecture included a discussion on sustainability in general and also a discussion on the LEED rating system. Because of time constraints, the discussion did not describe every possible LEED point, but rather discussed the different categories within the system, the intent of each of those categories, and the number of credits that were possible in each system. This gave students a general understanding of the types of topics that are considered in the LEED point system and the relative importance of each topic according to LEED.

Additionally, students were given the opportunity to take a guided tour of the SALA building that would eventually be used as the existing building to improve in this design challenge. The guided tour was intended to give students an overview of the building and the sustainable design features that contributed to its LEED gold rating. The tour also included anecdotal stories about what aspects of the design have worked well and which have not worked as well as intended.

**Data Collection**

To assess the challenges and benefits associated with this form of education, several assessment methods were used. Prior to students completing the design activity, but after the in-class LEED lecture and SALA building tour, students completed pre-tests to gather information about their understanding of LEED and sustainable design concepts as well as basic demographic information. The responses to the pre-test questions were important to gather because, in semesters prior to this design activity, the in-class lecture and sustainability tour were the only aspects of this first-year course intended to introduce sustainability concepts.

After the design activity, post-tests were taken by the students to assess some of the same types of questions related to sustainable design concept understanding. The responses to these questions were compared before and after the activity to identify areas where improvement was observed and areas where no improvement was apparent. In addition to these content understanding questions, questions were also asked to generate feedback about the experience itself. Students were asked to what degree they enjoyed the design activity, to what degree they felt it was beneficial for their education, and to what extent they were more interested in sustainability from the activity, to name a few of the questions asked.

Finally, after the pre and post-tests, students were given the opportunity to participate in a focus group discussion session. These sessions allowed for face-to-face discussions to provide feedback about the activity. This mode of interaction, while not anonymous, allowed students to bounce ideas off one another and agree or disagree with each other as well.

## RESULTS

During this activity, 22 first-year engineering students participated in the activity and completed all assessments. Five of the participants were female and all participants were between the ages of 18 and 20 years. The design submissions were analyzed to determine common trends. Figure 3 shows two examples of designs that were submitted by students to illustrate a general level of design completion. Additionally, this figure shows how different students elected to use different images to illustrate their design. The image on the left shows the work of a student who elected to use the image with no background and the image on the right shows the work of a student who elected to use the image with a dimmed background. In addition to the analysis of the submitted designs, the completed


**Figure 3: Examples of design submissions by students, including an example where a student used the image with a dimmed background (left) and one with the image with no background (right).**

pre and post-tests were examined to identify areas where there were significant changes in the students' performance and also areas where there was little or no evidence of change.

**Design process analysis**

In upper level design courses in the Architectural Engineering curriculum, students are generally encouraged to create design solutions through the exploration of several possible design concepts. This process allows students to weigh the pros and cons of each concept, and after this analysis, refine their design to one concept. For this work, it was initially hypothesized that the multiple provided images would encourage students to go through more than one design concept in arriving at their final design choice. This was largely not the case. The majority of the students (63%) completed this design activity through the creation of only one design concept. While this percentage was not as high as anticipated, the students who completed this implementation of this design activity did create more design iterations than prior semester's students who were provided with only blank paper to illustrate their design concepts. A two-proportion t-test showed that the proportion of students who created more than one design iteration was significantly higher in this second implementation of this research ($p=0.02$). In the first implantation of this work only 13% of the students went through multiple design iterations in arriving at their final design choice. In this follow-up research 37% of students went through multiple design iterations.

In prior work (Ayer et al., 2012), it was observed that some students deviated from the assignment. While students were tasked with redesigning the curtain wall of the existing building to make it perform more sustainably, 20% of these students deviated from this particular building element and modified, for example, the building roof, structure, or landscaping. In this follow-up implementation, it was observed that none of the students deviated from the particular building element of interest. A two-proportion test showed that this was a statistically significant decrease in deviation from the assignment topic ($p=0.015$).

In addition to the analysis of the number of design iterations that students completed in arriving at their final design, it was also of interest to examine which of the two provided images students used to illustrate their design idea. The two images, shown in Figure 2, allowed students to illustrate their idea in the context of the existing curtain wall design or with the existing design removed from their view. The design submissions from the students were grouped into one of three categories: those that used the image with the dimmed background, those that used the image with the background removed, and those that used both images in illustrating their design ideas. It was found that 43% of the students used the image with the dimmed background, 33% of students used the image with no background, and 24% of students used both images. Even when comparing the students who used the dimmed image with those who used both images, which was the greatest observed difference among the students, there was no statistical evidence suggesting any difference in preference between the images, which illustrates the varied learning preference among the students.

**Analysis of learning outcomes**

Prior to the design activity, students were asked several questions related to sustainability knowledge in buildings. Many of the questions that were asked on the pre-test were also asked on a post-test to identify key aspects of students' understanding that may have been improved as a result of this design activity. Several of these questions were open-ended in nature. To grade these responses, a score of zero, one, or two was assigned to each answer. A score of zero, meant that a given response was not a plausible answer to the question. A score of one was given to responses that were partially correct, but either partially flawed or not specific. Finally, a score of two was given to responses that provided a plausible example or explanation to the question.

One of the questions posed to students asked them to identify a drawback of the LEED® point system. Several students were able to provide specific examples of how the LEED system may have certain drawbacks. For example, some students made a comment about how LEED does not take into account the length of life of a particular facility. Currently a building that is being designed to last for 10 or 100 years would be eligible for the same points according to LEED and the fact that the longer building would not have the extra environmental impact with as many demolitions and subsequent reconstructions as the shorter lifecycle facility, would not gain any additional points. While 18% of the students were able to provide a plausible example of a drawback of the LEED point system before the activity, there were also 18% of the students who provided a plausible example of a drawback after the activity. There was no evidence to suggest that any significant improvement in LEED system understanding was observed in this activity.

Another question that was asked to students before and after the design activity was to identify an example of a specific building design strategy that, in some way, addresses sustainability. Scores of zero (completely incorrect), one (partially flawed or vague), or two (plausible example) were assigned to the responses to this question. Prior to the design activity, 59% of the students were able to identify a specific building strategy. After the activity 77% out of the students were able to provide a specific example. While this might suggest an increase in performance by the students, the small sample size does not provide a significant confidence level to this test ($p=0.17$).

**Students' feedback about the design activity**

In addition to the results that were generated through analysis of the submitted student designs and the assessment of pre- and post-test questions, data was also obtained from the students based on their opinions of the design activity. Several Likert scale questions were asked to students to determine to what extent the agreed or disagreed with particular statements. Based on the results of these questions, it was observed that students generally enjoyed completing the design activity, with none of the students saying that the activity was actively *not* enjoyable. The experience also helped to generate more interest in sustainable building design and the building design process among the participating students.

## CONCLUSIONS

The data collected in this research was analyzed to identify key learning aspects related to building sustainability and the building design process where students appeared to improve and also aspects where no improvement was observed. Prior to completing this work, it was hypothesized that there would be a significant improvement in students understanding of certain building sustainability topics. The responses to the questions designed to elicit response related to building sustainability knowledge and the LEED® point system did not indicate any statistically significant improvement. This will be a targeted aspect of student learning that future work will seek to improve.

While there was not a significant benefit observed in students' understanding of building sustainability practices and the LEED point system, there did appear to be some improvement in the students' design process that they employed to arrive at their design solutions. Students used both of the different images that were provided in the assignment to illustrate their design ideas. As compared to prior work (Ayer et al., 2012), students tended to focus more on the design problem at hand with the addition of the provided images which helped students focus on the portions of the particular building element in question. Students were also more likely to experiment with more than one possible design idea in arriving at their final design choice. This may be due to the inclusion of several images in the provided assignment materials. Finally, the activity offered benefits to the students in that it was an enjoyable activity that generated additional interest in sustainability and the building design process among the students.

## FUTURE WORK

The findings of the work presented in this paper will provide insight to help guide future research efforts. As a follow up to this paper-based activity that students completed, a computerized augmented reality (AR) application is being developed and implemented to understand how AR technology may allow students to create sustainable building designs better or faster. The findings from this work will serve as a baseline from which to compare the findings from the future AR implementations.

Augmented reality is a subset of mixed reality, which merges the real and virtual worlds through the use a computerized interface that superimposes virtual content onto a view of the physical world (Milgram and Kishino, 1994). It is hypothesized that this technology may show improvement in engaging students and encouraging them to experiment with even more possible design ideas before they arrive at their final idea as compared to the findings of this paper-based research. With the rapid computing ability of mobile computers, basic simulation equations will generate tailored feedback for students to view about their specific design choices. This is predicted to increase students understanding of the LEED® point system and the performance implications of different configurations of building systems.

The development of this application is currently underway. Figure 4 shows an initial prototype of the computerized AR application that is in development. Currently the application is using the Apple iPad platform as the mobile computing device for facilitating AR. Students will interact with this device to generate possible designs for the SALA curtain wall. Students will view their design ideas first in a 2D view similar to the method for viewing designs used in research presented in this paper. After students develop an initial design idea, they will be able to view their design idea in the context of the existing space by holding the device to view a marker that will be placed on the SALA curtain wall. This will give students the impression that they are viewing a full-scale prototype of their design. They will be able to physically navigate around their design to determine the effectiveness of the layout. After students are satisfied with their design decisions, the computing device will generate simulated performance values for the students to assess how their design worked.

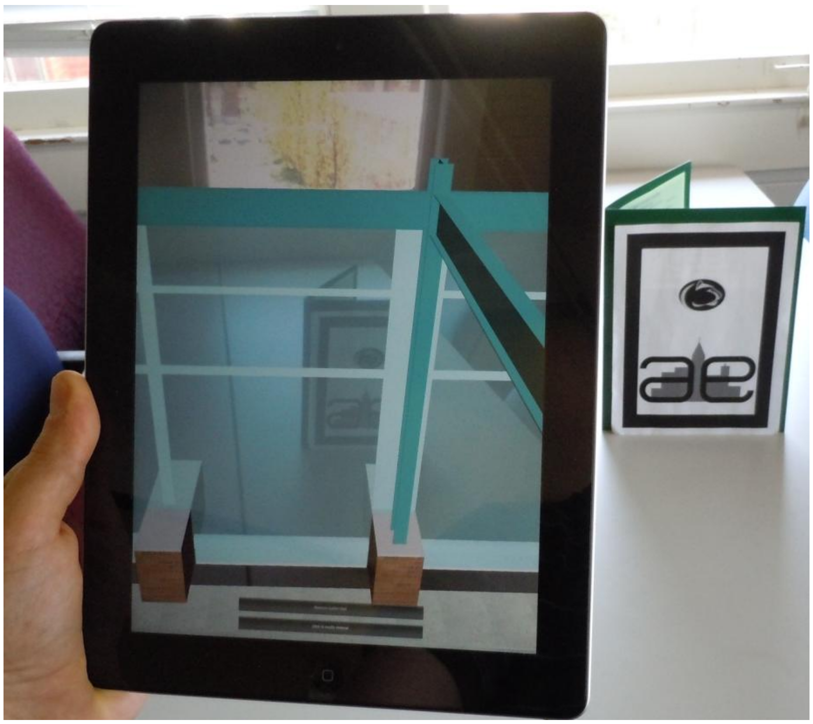

**Figure 4: A computerized augmented reality version of the design activity presented in this work is currently in development.**

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# RESULTS OF A PILOT MULTIDISCIPLINARY BIM - ENHANCED INTEGRATED PROJECT DELIVERY CAPSTONE ENGINEERING DESIGN COURSE IN ARCHITECTURAL ENGINEERING

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In August of 2009, the Department of Architectural Engineering (AE) at Penn State University launched a three-year multidisciplinary Building Information Modeling (BIM) enhanced Integrated Project Delivery (IPD) Capstone Project Pilot Program under industry and institutional sponsorship. Consisting of a year-long two course sequence this capstone initiative was organized and managed around multidisciplinary teams of architectural engineering students incorporating IPD/BIM concepts as an alternative to the traditional (individual student projects) Penn State AE capstone program known as AE Senior Thesis.

This paper describes the results of the first three academic years of what has become an ongoing effort to provide a multidisciplinary team collaborative student experience as a part of the fifth or professional year in AE at Penn State. In each of the three years, the pilot program incorporated three teams which consisted of one student from each of the four Penn State AE disciplines: Construction, Lighting/Electrical, Mechanical, and Structural Engineering.

Included in the discussion is a description of how students participated in this initiative working together in a collaborative atmosphere using BIM technologies and IPD techniques to investigate alternative designs and perform detailed engineering analyses based on a major building project selected from industry. Lessons learned and course management techniques developed that the authors feel are of value to other academic programs involved in incorporating IPD/BIM into some aspect of their curriculums is presented as well as suggestions for academic industry partnerships of this nature which are of value in preparing students for industry careers.

Keywords: Building Information Modeling (BIM), Integrated Project Delivery (IPD), capstone design, engineering education, architectural engineering, problem based learning (PBL)

## BACKGROUND / INTRODUCTION

The process of designing, constructing and operating a building facility in the architecture, engineering and construction (AEC) industry today is an increasingly complex task that involves a wide range of practitioners and a tremendous breadth of knowledge and skills. In conjunction with this process, IPD continues to be an important delivery concept in conjunction with the use of BIM technologies serving a supporting role.

In response to the shift toward BIM-enabled projects in industry, many academic institutions are considering or beginning to teach BIM in programs such as architecture, architectural engineering, and civil engineering. BIM-enabled or BIM-enhanced programs, often combined with IPD concepts, show promise for educating the next generation of engineers and project managers in how to navigate and manage the ever increasing complexity of the building industry .

Typically student engineering capstone design projects are introduced and depicted roughly at the Schematic Design (SD) or Design Development (DD) phase which is similar to the point in the actual project (outside of academia), where it would be presented to the client for design approval (Livingston 2008). Architectural design studios on the other hand, commonly work almost exclusively in the SD phase. The reality for students involved in BIM-enhanced projects is that they must almost immediately address design questions that are generally associated with the DD phase of a project or later (Denzer and Hedges 2008). BIM also creates the opportunity for students to introduce the element of time into their designs, as a result of the phasing and planning options which are included in most BIM project management software applications. IPD also is affected by the addition of a time factor because a key component of IPD is group collaboration at virtually all stages of design. Thus, the introduction of time and how to properly manage it is a necessity of a modern capstone student project.

In the general sense, the advantages of incorporating BIM into an educational setting have been documented in the AEC industry literature. They include specific features such as the ability to review and detect code compliance, perform advanced analysis from architectural models, coordination and integration of the work by various trades and engineering disciplines, check construction staging and scheduling and perform advanced engineering modeling and simulations (Denzer and Hedges 2008; Sharag-Eldin and Nawari 2010, Holland et. al 2010, Messner et. al. 2010)

# IMPLEMENTATION & ORGANIZATION

## Current Trends and Methods in Teaching BIM in Architectural Engineering Curriculums

The number and types of methods for teaching and integrating BIM into building related architecture and engineering related curriculums is as varied as the AEC industry itself. Practice-based engineering capstone projects alone experience numerous barriers that influence how they are incorporated into engineering curriculums (Dougherty and Parfitt 2009). BIM-based capstone projects do little to ease the barriers of this style of course. On the contrary, they are likely to add stress to such critical issues as: increased class sizes, allocation of faculty resources, and the decreasing knowledge base of university faculty members who possess extensive practical experience in the various engineering disciplines.

Among other information items, Mitchell (2010) performed interviews and surveys of the AE departments in the US during the academic time period of fall 2008 and spring 2009 resulting in a representative snapshot of what the various ABET AE departments were doing relative to the use of BIM in their academic programs. Reviewing the information gathered by Mitchell, the authors found that in the majority of AE departments, including Penn State, the implementation of BIM is still in the early stages. As noted, there is no one standard method of introducing BIM into an academic curriculum and often no uniform approach in those cases of how BIM is being implemented. The methods of BIM implementation currently in use in AE academic programs cover the full range from individual dedicated course offerings of a single discipline to curriculums that include multidisciplinary teams or participants in a program environment linked together through multiple courses often requiring IPD and BIM related prerequisites.

## Multidisciplinary BIM - Enhanced Capstone Project Program – AE Senior Thesis

As previously indicated, in 2009 AE launched a three-year IPD / BIM Capstone Project Pilot Program under industry and institutional sponsorship which consisted of a year-long two course sequence pilot program. The capstone pilot was organized and managed around IPD/BIM concepts using multidisciplinary teams of four AE students, one each in the construction, lighting/electrical, mechanical and structural disciplines. The IPD/BIM capstone project was implemented as a two semester project with students devoting four academic credits to the program each semester which represents about 25% of the student course credits for the year. (Solnosky 2011)

Case studies selected for the pilot ranged from a high profile iconic type high-rise building in New York City the initial year to a large university science laboratory complex with unique architectural features the second year to a collegiate hockey arena for the final year. In addition to a team of faculty coordinators, the student teams were externally assisted to various degrees by practitioner representatives from the actual project teams who provided background information, owner criteria and base line comparison information for student solutions.

Fall semester incorporated the case study / PBL learning format whereby students studied the assigned building and other related projects of the same building categories. Several types and formats of BIM models were created, modified, and integrated into various analytical applications, construction planning, visual aesthetic applications, and presentation visuals by the student teams. To help organize their workflow, each team went through the exercise of creating a customized BIM Project Execution Plan (CIC 2009) for their group with an emphasis on the design and construction tasks they wanted to investigate or emphasize during the remaining phases of the capstone project. The general schematic process of creating a BIM Project Execution Plan is shown in Figure 1.

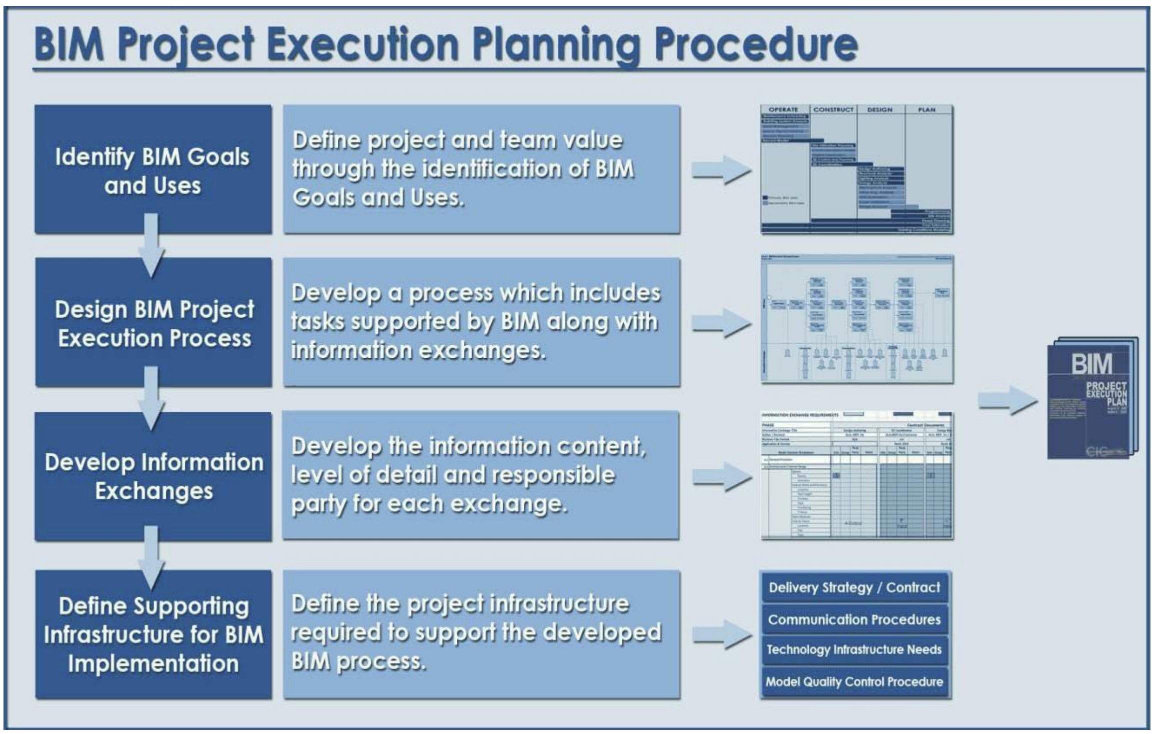



**Figure 1**
Schematic Outline of the BIM Project Execution Planning Procedure

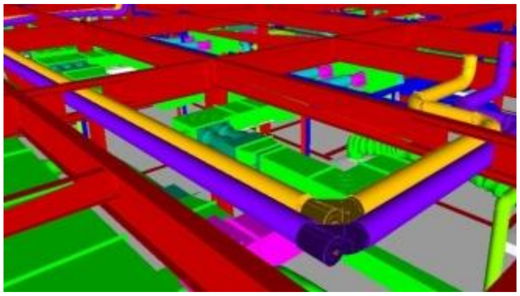
To assist the student teams in accomplishing this task, an introductory training session on the generation of customized BIM execution plans was provided to each team by faculty and graduate students familiar with the BIM execution planning process. Each IPD/BIM group supplemented their BIM execution plan by creating coordinated individual team goals, milestones and work plans based on such activities as discipline coordination, project phases or planned project deliverables. Regular collaborative meetings were set up early in the planning phase of the project in order to discuss expectations and confirm goals for the IPD process as a whole and to develop specific criteria for the various BIM models to be implemented. Figure 2 is a list of goals that the first year competition winning team created early on in the IPD/BIM planning process.

| Priority (1-3) | Goal Description | Potential BIM Uses |
|---|---|---|
| 1- Most Important | Value added objectives | |
| 1 | Alternate Shading Techniques and Glazing | Energy Analysis, Lighting, Cost, design reviews, VM, DA |
| 2 | Increase the constructability of the façade | Structural, cost, phasing |
| 2 | Increase the comfortability of the building occupants | Lighting analysis, mechanical, cost analysis |
| 2 | Capture solar energy for heating degree days | Energy analysis, lighting analysis, Mechanical |
| 1 | Cost analysis of the façade for each design change | Cost, DA, DR |
| 1 | Keep the aesthetic appeal of the façade | DR, Programmingm Existing conditions |
| 1 | Decrease floor to floor height in order to add additional floors | DR, Programming, Cost, phasing, structural, 3D coordination, DA, Mechanical |
| 2 | Look at how to obtain a zero grid energy building | Mechanical, lighting, electrical, energy analysis, cost,site analysis |
| 3 | Utility cost analysis (cogen, natural gas, electricity) | Mechanical, lighting, electrical, energy analysis, cost,site analysis |
| 1 | Optimize the CoGen plant | Mechanical, lighting, electrical, energy analysis, cost,site analysis |
| 1 | Lateral system alternative | structural, cost, 3D coordination, DR, DA, Code validation, construction system design |
| 2 | Investigate serviceability of the structural system | Code validation, 3D coordination, cost, structural |
| 3 | Investigate the updated codes of NYC for concrete/steel **union** issue | No BIM |

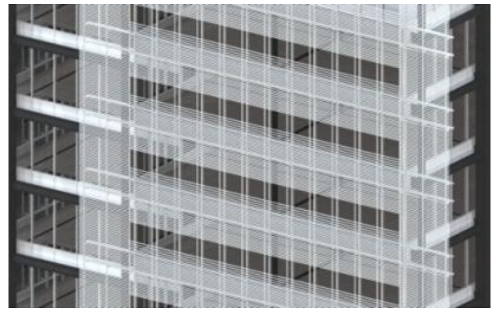
**Figure 2**
**Student Team Creation of Goals, Priorities and the Relationship to IPD/BIM Activities**

Students were also encouraged to include a BIM use analysis in their planning by evaluating potential work tasks related to design authoring, design review, 3D / 4D coordination and phase planning. Given limited time resources, this exercise assisted the student team in identifying those areas of BIM modeling and coordination that would benefit them the most relative to meeting their project goals.

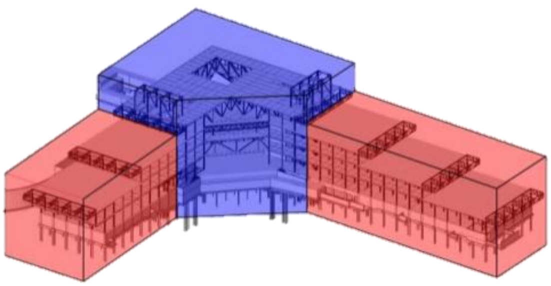
Existing conditions review, systems research, schematic and preliminary analysis performed in the fall semester culminated with a written proposal which was verbally presented and defended to the course instructors. During spring semester, each student team was responsible for the execution of a number of proposed alternative designs related to engineering and construction alternatives with an emphasis on team goals in an IPD format. These tasks included such timely topics as alternative envelope design, construction and optimization of building lateral framing systems, efficient mechanical and lighting / electrical system design, energy and sustainability concepts, constructability and various aspects of design and construction costing and coordination. Figure 3 contains representative examples of various student generated BIM models and supporting graphics created as a part of the pilot program and the tasks noted.



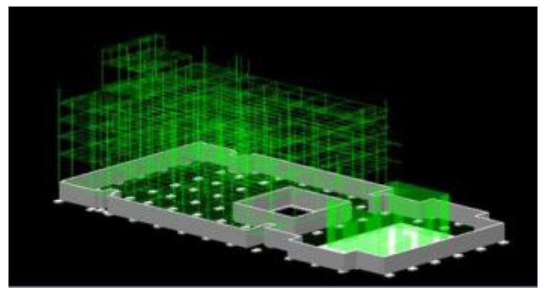
a). Ceiling Plemun Model



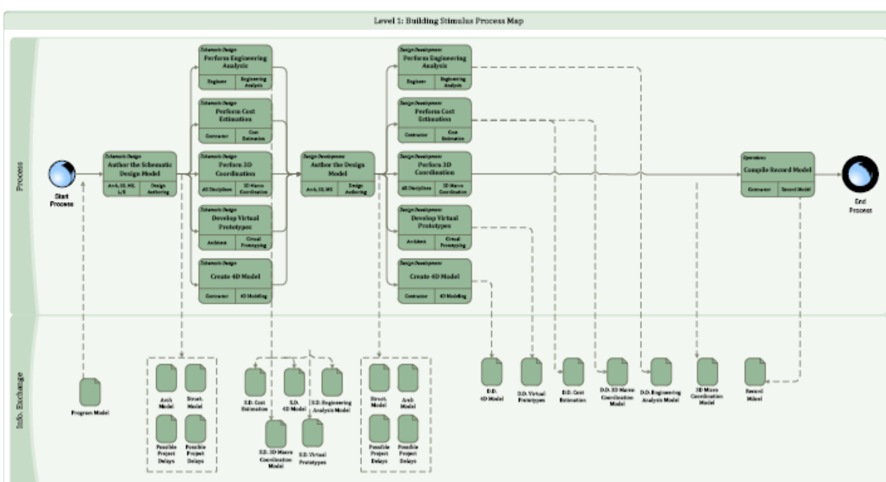
b). Exterior Façade Model



c). Conceptual Structural Hybrid System



d). 4D Sequencing Model for Construction




e). Process Map Generation for BIM Ex.

**Figure 3:**
**Student Generated Course Deliverables Integrating BIM and their Disciplines**

At the end of the academic year, all IPD/BIM student teams prepared a comprehensive written final report and group presentation to which they presented their project findings first to a jury of faculty and peers and then to an invited outside jury of practitioners. This process was conducted in a competition format culminating in the selection of the top student team and presentation of awards. Using a jury format also offered an invaluable opportunity to gather comments and suggestions from students, faculty and practitioners alike. Lessons learned from managing the pilot each year were gathered, reviewed for best practices course improvement purposes and appropriate changes were implemented the following academic year.

## WHAT DID WE LEARN ABOUT THE MANAGEMENT OF A BIM-ENHANCED MULTIDISCIPLINARY TEAM CAPSTONE PROJECT?

In terms of the day to day operations of teaching and managing the pilot project numerous items came to our attention, most of which were minor including such items as how do we deal with large file sizes and our current servers etc. Those types of items were dealt with on an on-going basis in the form of continuous improvement and best practice upgrades to the course. Not all lessons learned were that simple and some decisions had unintended results. A summary list of the more overarching lessons that may impact educational programs who are considering starting or expanding similar BIM-enhanced multidisciplinary team courses are discussed below.

- Faculty time for the course administrators increased, rather than decreased compared to the traditional (individual) Penn State AE capstone course.

- Some aspects of the faculty individual discipline advisor's time was decreased (Fall Semester) when all students were investigating the same basic issues on the same building project but increased (Spring Semester) when each team was working independently in a competitive format exploring different options for building system solutions. In year three, when the format was modified to provide students with a more schematic project rather than a constructed or nearly constructed building, advisor time increased once again due to the many alternatives being considered by the students.

- The concept of breadth learning or breadth experience in disciplines other than the student's primary discipline (a requirement of all capstone courses at Penn State) was greatly enhanced with the multidisciplinary team program. This may well be one of the most important gains from the team version of the capstone. In addition, students agreed that learning about design and construction coordination in this manner was much more meaningful than by way of the traditional breadth assignments used in the individual capstone project format.

- Most practitioners watching the presentations strongly indicated that the team program should be expanded to include more students in the future. However, after three years of the pilot and a fourth year competition pilot extension, many faculty feel that the team version of the capstone is not in the best interest of all students. They support multidisciplinary team learning but stopped short of indicating that it must all occur in the capstone course. Tradeoffs relative to the traditional individual capstone were acknowledged by all involved.

- Industry practitioner representatives reinforced the importance that students should be exposed to current BIM technology, planning and information management techniques and discipline specific software, if for no other reason than to begin to learn the limitations of the software.

- Students felt that completion of the BIM-enhanced team pilot made them more marketable to the profession.

- Practitioner jury members indicated that they saw evidence that the student teams were well aware of the standard deliverables and related coordination and timing needed between people (disciplines) as a part of the BIM modeling process.

- Students participating in the pilot overwhelmingly felt those involved had an excellent experience that permitted them to see firsthand how an integrated project team works together to achieve a common goal.

- A dedicated collaborative workspace, including computer hardware, provided for the teams is a necessity for a multidisciplinary BIM-enhanced team capstone.

- Since the student building projects used for the pilot to date have been high profile buildings designed and engineered by some of the top firms in the world, students sometimes found that it was difficult to find technical topics for exploration that had not already been studied (at least conceptually) by the original design teams or implemented into the existing building. The use of a more schematic design phase start in the 3rd year showed promise for addressing this concern.

- Faculty and students confirmed that the practice of exposing students to BIM related software in courses prior to the capstone in conjunction with "just in time" seminars (by vendors or others) was an effective way to learn the technology so it could be applied in the capstone. It permitted students to concentrate on the engineering concepts without being overly burdened with learning to run various software packages and translators.

## The Jury is Still Out: Areas for Future Ongoing Assessment

- Some students and faculty felt the buildings selected for the pilot program were too large and complex given the additional requirements of incorporating IPD, BIM and team coordination into a four person team. Others were convinced that smaller less complex buildings would fail to provide enough of an engineering challenge. This opinion varied within the disciplines.

- There was awareness and a concern initially that some of the students on a team would have more work than others and that the peaks and valleys (lead and lag times) could vary considerably. Students felt that additional assistance or attention by the faculty in helping to lay out the team goals and expectations is important to help them determine schedules and estimate workloads.

- AE may be trying to put too much content into one course. There may be other locations in the curriculum for multidisciplinary team experiences and/or additional prerequisite courses may ease the heavy student workload requirement.

- Given the cross disciplinary nature of many of the courses identifying effective times to conduct the courses that will accommodate the schedules of all students and faculty involved appears to be problematic. Common times for progress team presentations and reviews were an on-going struggle throughout the pilot.

In general all three years of the pilot used projects that were at slightly different levels of construction. The first year being completely finished, the second was under construction and the third year project was provided to the students just beyond the SD phase. All three start points turned out to be effective in achieving the learning objectives of the capstone program. The earlier stage projects provided more opportunity for freedom of exploration of topics while the more complete buildings revealed the complexities of the design and construction operations that students may not have discovered on their own without such an example.

## SUMMARY

Techniques, plans and methods of implementation of BIM in an academic setting, let alone a capstone course, are extremely varied as this is to be expected when a groundbreaking new technology is being introduced in the profession, let alone academia. The specifics of what works in one academic program are not necessarily that which will work at another. However, the authors believe that any institution planning the implementation of BIM in a capstone engineering design course will encounter similar experiences and barriers to those presented in this paper and will benefit from a review of this case study and suggestions related to executing a BIM-enhanced capstone offering.

When discussing case studies as specific examples of implementations of BIM technology, it is easy to lose sight of the fact that the most important aspect of teaching students to use BIM is not related to specific software or various modeling techniques. The key is learning to manage the technology and the vast amounts of information needed for implementation of a successful BIM-based project. Of particular concern and benefit to the students, is the lead-lag recognition of how the other disciplines depend on each other for the type and timing of information in a modern building project. This holds true for industry as well as the engineering classroom.

## ACKNOWLEDGEMENTS

The authors wish to acknowledge the time and effort of all AE faculty involved in the offering and management of the IPD/BIM pilot capstone project as well as the many industry practitioners and organizations that provided time and information to the students. Specific gratitude goes to The Thornton Tomasetti Foundation and the Leonhard Center for the Advancement of Engineering Education at Penn State for their efforts and funding support.

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# CAUSES OF CONSTRUCTION DELAYS FOR ENGINEERING PROJECTS IN THE MIDDLE-EAST: AN EGYPTIAN PERSPECTIVE

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## ABSTRACT

The construction industry in the Middle-East in general and in Egypt in particular has an important role in the economic growth of these countries. However, time overruns is a repetitive phenomenon in these construction industries. Very few studies addressed the causes of construction delays for construction projects in this area. This paper focuses on the causes of construction delays in the Egyptian construction industry.

The first main objective of the research is to identify and rank the major causes of delays for engineering projects. The second main objective is to determine the party responsible for the main causes of delays.

The research was conducted in three phases. The first phase included unstructured interviews with practitioners involved in the Egyptian construction industry. The second phase consisted of a survey for a sample of thirty-five (35) professional experts using a customized questionnaire. These experts represented the different parties of the construction industry; namely, the Contractor, the Employer, and the Consultant/ Project Manager. The third phase of the research covered the analysis of the data collected, in order to determine the frequency and ranking of the causes of delays. The analysis of the results also included the party responsible of the different causes.

The results revealed that the causes of delays can be grouped into five (5) main categories:
1) Construction related causes
2) Managerial related causes
3) Political related causes
4) Financial related causes
5) Technical related causes

The top 12 causes included 3 construction, 7 managerial, 1 political and 1 financial related causes. The contractor and the Employer were found to be responsible each of 5 of the top 12 causes. The remaining two were found to be the responsibility of a third party

## INTRODUCTION

The construction industry in the Middle-East in general and in Egypt in particular has an important role in the economic growth of the countries. It contributes an important percentage of the Gross Domestic Product. Moreover, it provides a significant portion of the employment opportunities. However, time overruns is a repetitive phenomenon in these construction industries. Very few studies addressed the causes of construction delays for construction projects in this area. This paper focuses on the causes of construction delays in large projects of the Egyptian construction industry, one the largest in the area and by far the one with the highest employment opportunities.

In evaluating the overall performance and success of construction projects, time is usually used as a major factor in such evaluation. However, completing a construction project on time is not an easy goal to accomplish. This is due to the complex and dynamic nature of the construction industry.

The first main objective of the paper is to identify and to rank the major causes of delays for engineering projects in the Egyptian construction industry. This is achieved by assessing the frequency and extent of the delays. The second main objective is to determine the party responsible for the main causes of delays.

## METHODOLOGY

The research was conducted in three phases. The first phase included unstructured interviews with ten (10) practitioners involved in the Egyptian construction industry for more than ten years. Two (2) of these practitioners had more than forty (40) years of professional experience.

These interviews along with an extensive literature review [1-10] were performed in order to identify the general and common causes of delays in construction projects. This phase resulted in developing a questionnaire that included thirty-one (31) possible causes for construction delays. They were grouped into five (5) main categories: 1) construction related causes (total 11) 2) Managerial related causes (total 10), 3) Political related causes (total 3), 4)

Financial related causes (total 4), and 5) Technical related causes (total 3). Table 1 presents the identified causes in accordance with their categories.

**Table 1: Major Categories of Delays and their Causes**

| NO. | CAUSE OF DELAY |
|---|---|
| **1** | **Construction Category** |
| 1.1 | Lack of Resources (Labor – equipment – material) |
| 1.2 | Change of priorities |
| 1.3 | Delay by nominated subcontractor |
| 1.4 | Delay by the employer's other contractors |
| 1,5 | Inspection |
| 1.6 | Delay in giving approval |
| 1.7 | Change in site / soil condition |
| 1.8 | Condition of existing structure |
| 1.9 | Delay in providing permanent utilities |
| 1.10 | safety rules |
| 1.11 | Bad workmanship |
| **2** | **Managerial Category** |
| 2.1 | Productivity |
| 2.2 | Lack of construction coordination & supervision |
| 2.3 | Stop Work Orders |
| 2.4 | Site acquisition |
| 2.5 | Joint venture coordination problem |
| 2.6 | Deficiencies in planning & scheduling |
| 2.7 | Low speed of decision making |
| 2.8 | Problem with neighbors |
| 2.9 | Work permissions |
| 2.10 | Labor strike (on site) |
| **3** | **Political Category** |
| 3.1 | Force majeure (Revolution / Public strikes) |
| 3.2 | Change of Law |
| 3.3 | Economic problems |
| **4** | **Financial Category** |
| 4.1 | Delay of payment |
| 4.2 | Contractor’s financial difficulties |
| 4.3 | Financial process |
| 4.4 | Inflation |
| 5 | **Technical Category** |
| 5.1 | Change of scope |
| 5.2 | Underestimating of construction method |
| 5.3 | Change construction technique to new unfamiliar one |

The second phase consisted of a survey for a sample of thirty-five (35) professional experts using a customized questionnaire. These experts represented the different parties of the construction industry; namely, the Contractor, the Employer, and the Consultant/ Project Manager.

The third phase of the research covered the analysis of the data collected, in order to determine the frequency and ranking of the causes of delays. The analysis of the results also included the party responsible of the different causes.

## METHODS OF DATA COLLECTION

As presented earlier, the data were obtained from the following three subgroups:

- Employers / Employers representatives - 6 participants.
- Consultants / Project managers - 6 participants.
- Contractors - 23 participants.

The criteria for the selection of the participants were based on the following guidelines:

- Employers or their representatives are to be involved in projects with more than L.E 300 million/year (US $50 million/year) in the last five years.
- Consultants and project managers have to be working for a registered consulting house of expertise as per the syndicate of Egyptian engineers or for a reputed international firm working in Egypt.
- Only contractors registered as first category according to the Egyptian Contractors Federation with a yearly volume of work more than L.E 300 million (US $ 50 million/year) were selected to be included in the sample.
- Individual respondents were selected to have a minimum of ten years experience in the Egyptian construction field.

The survey questionnaire was divided into three main sections. Section one included the general data about the respondent and the surveyed project. Section two included specific data about the project concerning project type, cost and time schedule. Section three included the identified major reasons causing delays of construction projects. A one-to-one interview with each respondent was arranged to fill each of the questionnaires.

## DATA ANALYSIS AND RESULTS DISCUSSION

The overall experts' feedback was collected and analyzed. Table 2 below lists the 31 causes of delays and their respective ranking, category, and the responsible party. A score was estimated for each class of respondents (Contractors, Consultants and Employers) as follows:

$$\text{Score} = \sum_{n=1}^{5} n \times \text{Frequency}_n \qquad [1]$$

Where n considered point scale. The scores of respondents are listed in Table 2.

Causes of delay have been grouped into three classes (High, medium and low) to identify the most critical causes that may lead to delay in construction projects. High rank factors are the ones that have weight above 125 while medium rank factors have a weight between 110 and 125 and low rank factors have a weight less than 110.

The results indicate that the contractor is responsible for about 40% of the causes of delays. Most of them are in the high rank group. The most common causes attributed to the contractor in the high rank group are lack of *construction coordination and supervision*, *productivity* and *lack of resources*. It has been found also that 50% of the managerial related causes of delay fall in the high rank category.

However it is noted that the highest number of causes is attributed to Employer. The most common cause of delay attributed to the Employer is *delayed decision making* and *delay in providing permanent utilities*. *Change of scope* and *payments delay* fall also in the high rank group.

The statistical results for each individual category revealed the following:

**1- <u>Construction Causes of Delay</u>**

The delays caused by the Contractor are identified as:

- lack of resources
- bad workmanship
- non compliance with safety rules
- delay by nominated sub contractor.

The delays caused by the Employer are identified as:

- change of priorities
- delay by employers' nominated contractors
- delay in giving approval

**Table 2- Ranking and Allocations of Related Causes of Delay (E: Employer, C: Contractor, E/C: Employer/Contractor, T: Third Party)**

| Rank | Category | Attributer | Cause of Delay | Weight |
|---|---|---|---|---|
| HIGH RANKING | M | E | low speed of decision making | 160 |
| | M | C | lack of construction coordination & supervision | 156 |
| | M | C | Productivity | 145 |
| | P | T | economic problems | 145 |
| | M | C | lack of resources ( labor- equipment- material) | 141 |
| | M | C | lack of coordination between contactor and design team | 140 |
| | C | E | delay in providing permanent utilities | 137 |
| | C | T | change in site/soil condition | 133 |
| | C | E | work permits | 130 |
| | M | C | deficiencies in planning& scheduling | 128 |
| | F | E | delay of payment | 128 |
| | M | C | low speed of decision making | 127 |
| MEDIUM RANKING | M | E | stop work orders | 124 |
| | F | C | contractor financial difficulties | 122 |
| | M | C | joint venture coordination problem | 121 |
| | C | E | delay in giving approval | 119 |
| | P | T | change of law | 119 |
| | C | E | delay by employer/other contractor | 118 |
| | C | C | bad work man ship | 118 |
| | P | T | force majeure (revaluation/public strike ) | 117 |
| | T | C | change construction technique to new unfamiliar one | 116 |
| | T | C | under estimating of construction method | 115 |
| | M | E | change of priorities | 114 |
| | C | E | condition of existing structure | 114 |
| | F | E | financial process | 110 |
| LOW RANK | C | C | delay by nominated subcontractor | 109 |
| | M | E | site acquisition | 109 |
| | C | E/C | Inspection | 107 |
| | C | E/C | problem with neighbors | 106 |
| | F | T | Inflation | 99 |
| | M | C | labor strike ( on site ) | 97 |
| | M | C | safety rules | 83 |
| | C | T | force majeure ( weather-earthquake- flood) | 76 |

- change in site conditions
- change of existing structure
- delay in providing permanent utilities

**2- Managerial Causes of Delay**

The delays caused by the Contractor are identified as:

- inadequate productivity
- lack of construction coordination and supervision
- joint venture coordination problems in the projects
- deficiencies in planning and scheduling,
- low speed of decision making
- labor strike on site for different reasons

The delays caused by the Employer are identified as:

- stop work orders directed to the contractor
- delay of handing over the site to the contractor in order to start mobilization
- delay of getting permits for both temporary and permanent works
- low speed of decision making.

**3- Political Causes of Delay**

The analysis shows that all political causes or factors that may occur during the construction phase are always beyond the control of project parties. Accordingly, change of law, economic problems and force majeure (revolution, public strike) are treated as third party responsibility. However, for economic problems some respondents tend to hold the employer or the contractor partly responsible for either the employer should cover these risks or the contractor should accommodate them within his risks.

**4- Financial Causes of Delay**

The two financial causes affecting the construction phase found to be attributed to the Employer were:

- delay in payment.
- financial processing.

Shortage of each flow on the other hand has been defined by respondents as contractor's sole responsibility. While price inflation is a commonly known cause which could be classified as third partly delay.

**5- Technical Causes of Delay**

The technical causes were few compared with construction related or managerial causes. The three main factors classified under this category are:

- change of construction method technique to new unfamiliar one,
- underestimation of construction methods

- change of scope.

The first two factors were found to be the contractor's responsibly while the changes of scope are the employer's sole responsibility.

El Gohary (2002) investigated specifically the construction delays in high investment projects in Egypt. Its findings showed that the major source of delay was *variations, contributing by 17% to the delays*. This was followed by design and engineering deficiencies contributing by 16% to the delays, financing problems by 12%, procurement and material problems by 10%, planning, scheduling, monitoring, and control factors by 10%, deficiencies in qualifications of contractors, subcontractors, consultants, and labor by 9%, coordination problems by 8%, deficiencies in organizational structure and resource allocation by 7%, project characteristics and external factors by 6%, and finally construction, QA/QC and site management deficiencies, by 5%. At least five causes of El Gohary study appear again in the top 12 causes of this study, namely; financing, planning, coordination, organization, and QA/QC procedures.

## CONCLUSIONS

The study focused on large engineering projects in the Egyptian construction industry. The medium and small size projects were not included in this investigation and could be a subject for future research.

The research was conducted in three phases; unstructured interviews and literature review to identify 31 common causes of delays, one-to-one questionnaire interviews with 35 professionals to adjust the list to the Egyptian construction industry, and analysis of the results to rank and allocate the responsibility of causes of delays.

The causes of delays were grouped into five (5) main categories:
1) Construction related causes
2) Managerial related causes
3) Political related causes
4) Financial related causes
5) Technical related causes

The top highly-ranked 12 causes of delays were found to be:

| |
|---|
| low speed of decision making by Employer |
| lack of construction coordination & supervision |
| Productivity |
| economic problems |
| lack of resources ( labor- equipment- material) |
| lack of coordination between contactor and design team |
| delay in providing permanent utilities |
| change in site/soil condition |
| work permits |
| deficiencies in planning& scheduling |
| delay of payment |
| low speed of decision making by Contractor |

This study show a similar trend to a study previously conducted on the Egyptian construction industry (El Gohary, 2002). The top 12 causes identified in this study included three construction causes, seven managerial causes, one political cause, and one financial related cause.

The Contractor and the Employer were found to be responsible for 6 and 4 of the top 12 causes, respectively. The remaining two were found to be the responsibility of a third party.

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# THE APPLICATION OF LEAN CONSTRUCTION TOOLS IN UNITED KINGDOM CONSTRUCTION ORGANISATIONS: FINDINGS FROM A QUALITATIVE INQUIRY

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Several Lean construction tools have been developed based on Lean principles to help improve productivity and minimise resources utilisation in building construction. Though Lean construction practice is centred around the same Lean principles, companies have tended to develop and adopt different tools. The study is aimed at identifying the different tools applied and the rationale behind the variation in the tools' selection and application. An exploratory qualitative study was undertaken using semi-structured telephone interviews with 7 key personnel from 7 contracting firms in the United Kingdom to investigate the Lean construction tools they apply and the rationale behind selecting and applying such tools. The interviews were transcribed verbatim, coded based on emerging themes and analysed using a thematic analysis approach. It was found that the tools selected were found to differ among the companies due to variations in the drivers for adopting Lean construction in the organisations. The analysis revealed 18 Lean tools and 19 drivers for adoption of Lean construction principles in these organisations. The main drivers were time and cost reduction, clients' satisfaction, efficiency, quality, health and safety, and process improvement. The study concludes that the drivers to Lean practise in an organisation play a role in determining what tools are selected and applied in the organisation. The findings reported will be of interest to companies in helping them to select the appropriate tools when adopting Lean construction in their organisations.

Keywords: Drivers, Lean construction principles, Lean construction tools.

## INTRODUCTION

Lean construction is gradually gaining global acceptance due to its positive and cost effective results (Matias and Cachadinha 2010). The adoption of Lean principles in construction has been growing in recent years especially in the current economic climate where major construction firms in the UK have to cope with low profit margins and high clients' demands. The Construction Lean Improvement Programme (CLIP) has even been introduced to guide UK construction organisations in applying the Lean concept across all stages of the project delivery (BRE 2010).

Lean construction practice is centred around the application of Lean principles in construction activities. Lean tools have been developed to aid the application of Lean principles. Though contracting organisations, engaged in Lean construction practice, adopt similar Lean principles, several organisations have tended to apply few varying tools. A critical analysis of case studies reported in Alsehaimi (2009), Skinnaland and Yndesdal (2010), and BRE (2012) reveal that organisations generally apply only one, two and at most four varying tools. These tools include Visual management, the Last planner system, 5S (house-keeping), design management, process mapping and 5whys (root cause analysis). It remains unclear why contracting organisations applying the same Lean construction principles tend to apply a few number of tools that vary across the organisations. In order to make this clear and provide a basis for selecting and adopting the tools, the research question "why do contracting organisations apply a few number of varying Lean construction tools?" is investigated. The rationale for selecting the tools could be a guide for organisations intending to apply Lean in selecting the appropriate tools. The paper reports part of the findings of a doctoral research investigating the health and safety impact of Lean construction practice in contracting organisations.

A review of the meaning of Lean construction and the different Lean tools applied is presented. This is followed by a discussion on the research methodology adopted, findings that emerged from the data analysis and conclusions.

## LEAN CONSTRUCTION

The Lean concept was developed by the Toyota car manufacturing organisation to minimise waste in the production process and deliver value to customers (Womack et. al. 1990; Womack and Jones 1996). The organisation focussed on delivering maximum value using the least possible resources (Abdelhamid 2004). The significant success achieved triggered the adoption of Lean thinking in non-automotive sectors.

Lean construction practice is centred on eliminating waste and sources of waste. There are different forms and sources of waste in construction. Ohno (1988) identified waste as defects to be amended; overproduction; inventory; materials transportation; unnecessary processing steps; unnecessary movement of employees; and waiting. Waste could also arise from the work methods, materials, labour, time, operations and equipment (Alarcon 1995). Furthermore, construction waste could be in the form of design errors, variations, rework, defects and excess material consumption. In addition to this, Abdelhamid and Everett (2002) suggested occupational accidents and poor health and safety as potential sources of waste of resources both money and labour. Song et al., (2008) also noted that waste could occur due to poor project organisation. Lean construction tends to minimise the different forms of waste through the application of Lean principles to the production process.

The five basic principles of Lean thinking are: value identification; value stream mapping; value stream flow; achieving customer pull; and striving for perfection and continuous improvement help in eliminating waste (Womack and Jones 1996; Mascitelli 2002; Koskela 2004). However, due to the peculiar nature of construction processes, which varies from manufacturing, Koskela (1992) outlines Lean construction principles as: reducing variability; reducing cycle times; simplicity; benchmarking; increasing output flexibility; and increasing process transparency. On the other hand, Farrar et al. (2004) considers workflow reliability as the main principle of Lean construction. Furthermore, Seneratne and Wijesiri (2008) identified the elimination of waste, obstacles to value stream flow and all non-value adding activities as the core principles of Lean construction. Based on these principles, several Lean construction tools were developed to aid the implementation of the concept in construction organisations.

**Lean Construction Tools**

The nature of construction project delivery processes differs from manufacturing in terms of the operations, nature of tasks execution and activities planning. Hence, Lean manufacturing tools cannot be directly applied in construction. In conformity with Lean construction principles, academicians and researchers have developed a range of Lean construction tools for use in practice, both within site and office working environments, mainly for the purpose of reducing project cost and duration, maximising efficiency and improving productivity and quality of products and services.

A number of studies have identified a range of different tools (Ballard 2000; Abdelhamid and Salem 2004; Salem et al., 2005; Alsehaimi et al. 2009; Lee et al., 2010). These include the last planner system, increased visualization, daily huddle meetings, first run studies, the 5S (house-keeping), error-proofing, Kanban cards, Failsafing, 5 whys (root cause analysis) and offsite fabrication. A critical review of  Lean application within 16 organisations (BRE 2012) showed that the tools mostly applied in the organisations include process mapping, visual management, collaborative planning and house-keeping.

Despite the potential benefits attached to these tools, the analysis revealed that the organisations generally apply few of them. Similarly, few tools seem to be applied in studies that reported application in numerous organisations (Salem et al., 2005; Alsehaimi 2009; Nahmens and Ikuma 2009; Skinnaland and Yndesdal 2010). This could be due to factors like implementation cost, familiarity with the tools, level of knowledge and training cost. Though the organisations apply the same Lean construction principles, it remains unclear why they tend to apply varying tools in addressing their problems. Hence, the research sought to investigate "why do contracting organisations apply a few number of varying Lean construction tools?" The findings will provide useful learning opportunities among organisations engaged or willing to engage in Lean construction practice. The appropriate research methodology adopted in carrying out this investigation is presented in the next section.

## RESEARCH METHOD

The nature of a research problem determines the kind of method to be adopted in the research. As an exploratory study, the research adopts an interpretive approach to build a holistic picture of the phenomenon based on the interviewees' personal experience, knowledge, understanding and textual description of the situation (Creswell 2009). Semi-structured interviews were conducted with Lean construction practitioners to get an in-depth description. In addition to its flexibility, a semi-structured interview was chosen to give the researcher chances to make further clarifications and obtain more details while the interviewees freely express their views and discuss at length (Bailey 2007). The interviewees were asked questions relating to their Lean construction journey, purpose of engaging in Lean construction practice, the kind of Lean tools they apply and the rationale for applying them. An invitation letter was sent to the organisations, who then appointed the interviewees to speak on their behalf. The interview was conducted on telephone to save resources. On the average, the interviews lasted for about 30 minutes each. In order to gain the participants confidence and trust, guard against inappropriateness and promote the research quality and integrity (Creswell 2009), the researcher identified ethics as a priority in conducting this research. An ethical approval was obtained from the School of Technology Ethics Committee at the University of Wolverhampton. Participants were fully informed about the aim and objectives of the research and they consented to voluntarily participate in the research. The entire research was conducted in a way that ensured that confidentiality and integrity of the participants were respected. The interviews were held between May to September, 2011.

Only contracting organisations engaged in Lean construction practice were targeted; thus, a purposive sampling technique was adopted (Neuman 2006). A list of contracting organisations engaged in Lean construction practice was collected from the Lean construction institute (LCI-UK) and the Construction Lean Improvement Programme (CLIP) website. Further, the snowballing approach was adopted by asking participants to refer the researcher to other organisations engaged in Lean construction practice and who would be willing to participate in the research (Bryman 2008). A total of 45 companies were invited to participate in the interview. However, only 7 construction practitioners from 7 companies participated in the interview.

The interviews were held with the Lean experts in the 7 organisations. Codes were assigned to each participant to maintain confidentiality. These personnel include: the Contracts manager (R1), Project manager (R2), Best practice manager (R3), Project leader (R4), Associate director/ Best improvement manager (R5), Lean improvement manager (R6) and Business improvement manager (R7). They are deeply involved in the whole Lean construction implementation journey of their organisations.

The interviews were analysed using a thematic analysis approach (Boyatzis 1998). The method is a suitable and flexible way of collecting and communicating ideas and patterns or themes that emerge during an interview (Aronson 1994). Furthermore, Braun and Clarke (2006) suggest that it enables the researcher to get a rich and detailed meaning out of the interview.

The interviews were recorded and transcribed verbatim to organise and prepare the data for analysis. The transcribed copy was read over and over to have a good understanding of the general ideas and identify the crucial ideas across the interviews related to the aim and objectives of the study (Creswell 2006; Flick 2009).

Codes were assigned to words, phrases and segments within the data which are relevant to the research question (Boyatzis 1998). These codes were then categorised into potential themes. The coded words and segments were studied, reorganised and collated under relevant themes (Braun and Clarke 2006). For instance, data extracts like "saving money", "cost benefit" and "reduce cost" were coded as "cost reduction" and categorised under the theme "drivers to Lean construction practice". The different themes that were identified from the interview are "Lean construction tools applied", "drivers to Lean construction practice ", "the challenges of Lean construction practice", and "the impacts and outcomes of Lean construction practice on the organisations".

The categorised extracts were further analysed to make a detail description of the different themes and patterns or relationships among them. This paper discusses findings related to the rationale for selection and application of Lean construction tools in the organisations.

## FINDINGS

This section discusses findings from the interview relating to the application of Lean construction tools in the organisations. The research is aimed at investigating "why do contracting organisations apply a few number of varying Lean construction tools?" It was carried out with participants from organisations of different sizes, engaged in different kind of projects across different locations within and outside the UK.

**Working experience in construction industry**

The level of working experience differs across the interviewees as shown in Table 1. R1, R4, R5 and R7 have over 30 years of working experience, while R3 has 18 and R2 and R6 have 4 and 5 years respectively. This reflects their rank in their organisations. The most experienced among them (R5) is also a part of the top management of their organisation. However, all the respondents are the experts of Lean implementation within their organisations and were all therefore considered being in a good position to discuss: the organisations' Lean construction journey, purpose of engaging in Lean construction practice, the kind of Lean tools they apply and the rationale for applying them.

**Organisation operations area**

The organisations' geographical area of operations varies as shown in table 1. Four of them focus and operate in wider areas, for example, R2 operates at a global level, while the other three organisations operate in smaller areas, for example R5 in Greater midlands. However, the organisations are willing to follow their regular clients beyond these areas of focus.

*Table 1: Sample characteristics*

| | Role | Work experience (years) | Operation areas |
|---|---|---|---|
| R1 | Contracts manager | 30 | North-west England |
| R2 | Project manager | 4 | Global |
| R3 | Best practice manager | 18 | Europe, Asia |
| R4 | Project leader | 32 | Birmingham |
| R5 | Business improvement manager | 34 | Greater Midlands |
| R6 | Lean improvement manager | 5 | Greater London |
| R7 | Business improvement manager | 33 | Birmingham, London, Warwick, Liverpool, Manchester |

## Lean construction tools applied in the organisations

The interviews identified 18 Lean construction tools across the organisations. However, some of the tools have already been identified in the literature review. Those already mentioned in the literature review are: 5S (house-keeping), 5whys (root cause analysis), continuous improvement, visual management, elements of Last planner system, kanban, standardisation, design management, collaborative planning, just-in-time, processing mapping, and daily huddle meeting. The additional tools identified from the interviews are: integrating planning and procurement, continuous improvement, knowledge sharing, suppliers' involvement, short term planning, problem solving tracker. However, suppliers' involvement could be part of collaborative planning while problem solving tracker could be part of root cause analysis.

The organisations generally apply few varying tools. Some of the contractors apply more than two Lean tools. For instance, R7 applies weekly work plan, collaborative planning, and root cause analysis (5Whys). Visual management concept is applied in different ways across the organisations. R5 apply it in the form of Pareto charts while R1 uses daily task objective charts to communicate vital information to workers.

The different organisations consider the application these tools as a suitable way of achieving their goals and attaining their targets on cost reduction, project duration, health and safety, productivity and profit margins. These are what drove them into engaging in Lean construction practice. Therefore, the drivers or purpose of engaging in Lean construction practice influence their decision in selecting only the appropriate tools they consider suitable in achieving their goals. The next section identified the drivers across the 7 organisations.

## The Drivers to Lean construction practice in the Organisations

The drivers for engaging in Lean construction practice differ across the organisations. The interviews identified 19 different drivers. Some organisations saw improving efficiency through Lean construction practice as a way of minimising cost and time. For example, according to R6, "… we had to do something that will reduce our cost and therefore efficiency is only where we can go ahead. So that is why we choose to go Lean construction".

The drivers identified in the interviews are: cost reduction benefits, improving efficiency, improving product and services quality, time reduction benefits, increasing revenues and profits, clients' satisfaction, health and safety, enhancing site conditions, enhancing image, improving presentation, delivering value for clients, becoming leading edge, economy, best practice, process improvement, market competition, making a difference, smooth project delivery, government reports.

These drivers seem to play a major role in the organisations' decision to apply the selected tools will be discussed in the next section. The organisations also limited the tools they apply to only those considered appropriate in addressing their purpose of engaging in Lean construction practice.

## DISCUSSION OF RESULTS

According to the interview findings, the organisations have different purposes or drivers for applying Lean construction in their organisations. Hence they select and apply only the kind of tools that would enable them to realise the targeted benefits of adopting Lean construction principles in the organisation. Consequently, the difference or dissimilarity in drivers or purpose of applying Lean construction seem to result in adopting different set of tools across the different organisations as illustrated in table 2 below. Hence, organisations with similar drivers tend to adopt some tools in common.

## CONCLUSION

Though the organisations apply the same Lean construction principles, they tended to apply few tools of varying type. A total of 18 Lean construction tools and 19 drivers were identified in the study. Yet tools like continuous improvement are considered to be principles in the current literature, some of the organisations consider it as a Lean tool. Also, some tools have similar benefits but they are applied in different ways and called with different names. Hence, there is need for more enlightenment on Lean terminologies among the organisations. Furthermore, since the organisations apply Lean for different purposes, the sharing of knowledge and experience could help the organisations to improve Lean practice. However, there is a need to have a common language for terminologies and definitions among Lean construction researchers and practitioners to facilitate understanding and sharing of information among the organisations.

*Table 2: Comparison of Drivers to Lean construction practice and tools applied in the organisations*

| | Drivers to Lean construction practice | Lean construction tools applied |
|---|---|---|
| R1 | Reduce project duration, Explore cost benefits, improve efficiency, Improve quality of end product reduce defects, enhance site conditions, improve safety and image/presentation | Standardisation of teams, product, designs and materials; Offsite manufacturing; Early elimination of un-controllable risks; Problem solving tracker; Daily task objective charts; Just in time |
| R2 | Deliver value for your clients, Become Leading edge, Increase revenues and profits (internally) | Sharing Knowledge and lessons learnt; Risk reduction; Kaizen (continuous improvement) |
| R3 | Client satisfaction, economise resources, best practice | Collaborative Planning; Short term planning; Process Mapping; Continuous Improvement of processes |
| R4 | Improve efficiency in processes, Reduce cost, Reduce time on site | Collaborative planning |
| R5 | Make more money, Clients' satisfaction, Improve quality, More efficient, Reduce cost, Smooth project delivery, Health and safety Make a difference, Government reports | Visual management (Pareto chart) Root cause analysis (fishbone diagram)<br>Collaborative planning; 5whys (Root cause analysis); 5S/5C (house-keeping); Workers empowerment |
| R6 | Improve efficiency, Reduce cost, Market competition | Design management; Root cause analysis; Collaborative planning; Integrating planning, programming and procurement; Weekly work plan (Last planner) |
| R7 | Improve product and services quality, Improve productivity, Deliver value to clients, Eliminate wasteful activities, Competitiveness, Government reports | 5S (house-keeping); Signs; Collaborative planning; Workers empowerment; Daily huddle meetings; Suppliers' involvement in decision making; 5 Whys |

Due to variations in the drivers for adopting Lean construction, the tools selected were found to differ between the organisations. Furthermore, only tools considered appropriate in addressing such driver were applied. Hence, the study concludes that the drivers to Lean construction practice in an organisation play a role in determining what tools are selected and applied in the organisation. The purpose of applying Lean construction is thus a significant criterion for selecting the suitable tools.

The findings could therefore help organisations intending to adopt Lean construction in selecting the appropriate tools to address their needs and drivers. However, the findings are limited to a study involving 7 UK contracting organisations. Though this may be a possible limitation to the study in terms of sample size, it is still within the sample range usually adopted for qualitative inquiry within the construction industry.

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# RELATIONSHIPS AMONG CONTRACTING PARTIES AND THEIR EFFECTS ON OUTCOMES OF PUBLIC CONSTRUCTION PROJECTS IN CHINA

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**Abstract**
Adherence to clear and equitable contract documents does not guarantee project success. Many other contributors such as attitudes of the contracting parties and their relationships are also considered important. Hitherto, it is not known if relationships among contracting parties in public construction projects in China have a significant effect on project performance. This study aims to investigate relationship quality among contracting parties and their effects on project performance in China's public construction projects. Using a questionnaire survey, 59 sets of data of completed projects were collected from public owners and private contractors and consultants in Beijing. The data were analysed using correlation analysis and one-sample t test. The results show that public construction projects to have achieved significantly good quality performance and client satisfaction but not in budget nor schedule performance. The results also that higher quality of relationships during project implementation stage always leads to significantly good project quality and client satisfaction with the project. In addition, the results show that relationships among contracting parties play an important role in successful project outcomes. It is suggested that concerted effort should be taken to improve relationships in publically funded construction projects, as this will lead to better project outcomes.

**Keywords:** Contracting Parties, Relationship, Public Construction Projects, Project Outcomes

## INTRODUCTION

In construction projects, the use of collaborative relationships for construction development has been advocated (Latham, 1994; Egan, 1998). The high level of team harmony could lead to increased project performance (Walker, 1998; Schwenk and Cosier, 1993). On the other hand, relationship conflicts arising from interpersonal problems, friction and personality clashes cause group members to work less effectively and produce sub-optimal products (Argyris, 1962). Rahman and Kumaraswamy (2002) argued that an appropriate contracting method with clear and equitable contract documents does not guarantee project success. Many other contributors are needed. For example, the attitudes of the contracting parties (Thamhain and Wilemon, 1987) and their interpersonal relationships (Pervan et al., 2011) are also considered important.

Problems of cost outrun and schedule delay are frequently reported in China's construction industry (Zou et al., 2007; Ling et al., 2009). Hitherto, it is not known if quality of relationships among contracting parties have a significant effect on project performance. The aim of this study is hence to investigate the quality of relationships among contracting parties and their effects on project performance in China's public construction projects. The specific objectives of this study are to: ascertain project performance levels in terms of cost, time, quality and client satisfaction; evaluate the quality level of relationships among contracting parties at the start, during implementation and at the end of the project; and investigate the extent to which relationships affect project performance. Relationship in this paper is taken to mean networking, personal connections, special relations or particularistic ties among contracting parties (Ling and Li, 2012).

Public construction projects are investigated because unlike private projects, project participants in public projects need to maintain arm's length relationship to avoid accusation of corruption. As China is a geographically large country, the research focused on the capital city Beijing, which has a significant number of completed public projects for the 2008 Olympics.

## LITERATURE REVIEW AND RESEARCH HYPOTHESIS

Project outcomes include the traditional basic triple project outcomes (completion within budget, on time and to an acceptable level of quality), safety performance, environmental performance, stakeholder satisfaction and profitability (Ling et al., 2004). This study considered it from the view of project delivery and organizational level competency. Under project delivery, the three main triple project outcomes were adopted as the performance metrics following Konchar and Sanvido (1998). For organizational level competency, service quality was operationalized as client satisfaction with the project following Ling et al. (2004).

It is suggested that networks emerge because of environmental turbulence comprising market fragmentation, short project life cycles, and project complexity and uniqueness (Katsanis et al., 1997). The construction industry could be considered as a dynamic network as there is a high degree of outsourcing and high extent of collaboration. Relationships are hence important to a construction project because the construction task requires interaction among contracting parties who need to perform interdependent sub-tasks (Landy and Rastegary, 1989).

Relationship in construction projects has therefore been a subject of much research recently. For instance, Akintoye and Main (2007) identified fifteen reasons why construction contractors can be involved in collaborative relationships; Eriksson and Laan (2007) studied the procurement effects on client-contractor relationships and found that construction clients should focus more on trust at the buying process; Pinto et al. (2009) adopted trust in projects as a tool to assess the client-contractor relationships; Ling and Li (2012) also found that network strategies are relevant to manage construction projects effectively.

The brief literature review reveals that there are benefits in having good relationships in a construction project. However, in the context of China, it is not known if prior good relationships with the public clients could lead to harmonious relationships during project implementation, and subsequently improved relationships at the end of the project. It is also not known if there are tangible benefits in good relationships such as improving a project's time, cost and quality outcomes. The fieldwork was thus undertaken to uncover the association between prior/on-going relationships and project outcomes.

In the context of this study, it is firstly postulated that better organizational relationships at the start (Y1), during implementation (Y2) and at the end of the project (Y3) would lead to better project outcomes, operationalized as cost performance (Z1), schedule performance (Z2), quality performance (Z3) and client satisfaction (Z4). This study also hypothesizes that better interpersonal relationships (Y4) would also benefit the project performance.

## RESEARCH METHOD

This paper reports a part of the results of a large research project that investigated the relevance of relational contracting in public construction projects. The data collection instrument is a structured questionnaire. Surveys were conducted from June to November 2011 in Beijing, Hong Kong, Singapore and Sydney. Respondents were requested to each provide data of a completed public sector project that they had been involved in. Objectives of the survey included evaluating the extent to which relational contracting practices were adopted in the project; and assessing the driving and impeding factors for adopting those practices. This paper reports a part of the study, focusing on relationships among contracting parties and project performance in Beijing.

In the questionnaire, the strength of relationship was rated by a five-point Likert scale (1 = Very low, 3 = Neutral, 5 = Very high). Respondents were also asked to assess the project outcomes: cost performance (1= > 5% budget overrun by; 3= cost same as budget; 5= > 5% below budget); time performance (1= > 5% late finish; 3= finish on time; 5= > 5% early finish); output quality and client satisfaction (1= expectations not met; 3= expectations met; 5= exceed expectations).

The population comprised public sector clients, private sector consultants (e.g. architects, engineers, quantity surveyors and project managers) and contractors, who had been involved in public construction projects in Beijing. Since there is no national registry of officials/firms involved in public construction projects, the size of the population is not known. The sampling frame for public officials was obtained from government directories. As the number of people in this group was not likely to be overwhelming, questionnaires were sent to all identified relevant public officials. The sampling frame for private consultants and contractors was derived from the respective professional and trade institutions. Random sampling was used to select the samples from these identified groups. It was anticipated that some of these would have colleagues and personal connections knowledgeable to participate in this research as well. Hence they were requested to recruit other possible respondents. It is acknowledged that samples from the private sector may include those who have not handled public projects. The questionnaire clearly stated that only those who had completed public projects should fill up the questionnaire.

The one-sample t-test procedure tests whether the mean of a single variable differs from a specified constant (SPSS, 2002). It was performed to ascertain if there are significantly good performance outcomes (Z1 to Z4) and relationships (Y1 to Y4). This is when $p < 0.05$ and the t-value is positive. If the t-value is negative and $p < 0.05$, the performance/relationship is significantly poor. To investigate the association between quality of relationships and project outcomes, Pearson correlation analysis was employed. It could be used to measure the strength and direction of the linear relationship between a pair of quantitative variables (SPSS, 2002). In Pearson's correlation analysis, each pair of variables comprised one of the relationship variables and one of the performance indicators.

## CHARACTERISTICS OF THE RESPONDENTS

Survey questionnaires were sent to 259 target respondents in Beijing. A total of 59 valid completed questionnaires were received, giving a response rate of 22.8%. The response rate was relatively low but statistical analysis could still be performed because in accordance with the generally accepted rule, central limit theorem holds true when the sample size is no less than 30 (Ott and Longnecker, 2001).

The characteristics of the respondents are given in Table 1. Please note that one respondent did not provide background information so that numbers in Table 1 are total up to 58. As shown in Table 1, the respondents have extensive construction experience in many types of public construction projects. The number of years of respondents' experience ranged from 2 to 30 years with an average of 11 years. The respondents' firms engaged between 25 and 160000 employees with an average of 19934 employees.

Table 1: Characteristics of respondents

| Characteristic | | Number | Percentage |
|---|---|---|---|
| Experience in construction industry | < 5 years | 8 | 14 |
| | 5-9 years | 14 | 24 |
| | 10-14 years | 22 | 38 |
| | ≥ 15 years | 14 | 24 |
| | Average | 11 | |
| | Min | 2 | |
| | Max | 30 | |
| Organization type | Government | 10 | 18 |
| | Engineering firm | 1 | 2 |
| | Architectural firm | 10 | 18 |
| | Quantity surveying firm | 5 | 9 |
| | Contractors | 32 | 57 |
| | Others | 4 | 7 |
| Ownership of organization | Public | 30 | 52 |
| | Private | 13 | 22 |
| | Joint Venture | 15 | 26 |
| | Average of public percentage | 45 | |
| Size of total workforce | < 100 | 12 | 21 |
| | 100-999 | 23 | 40 |
| | ≥ 1000 | 22 | 39 |
| | Average | 19934 | |
| | Min | 25 | |
| | Max | 160000 | |

## RESULTS

The first objective of this study is to evaluate project performance levels in terms of cost, time, quality and client satisfaction. One sample t test results in Table 2 show that public construction projects in Beijing achieved significantly good performance in client satisfaction (3.32, p=.000) and quality performance (3.19, p=.002), but had significantly poor cost performance (2.24, p=.001) and time performance (2.52, p=.029).

Table 2: One sample t test results

| Variables | | Mean | T Value | Sig. |
|---|---|---|---|---|
| Project Outcomes | Cost (Z1) | 2.24 | -3.376 | 0.001 |
| | Time (Z2) | 2.52 | -2.246 | 0.029 |
| | Quality (Z3) | 3.19 | 3.296 | 0.002 |
| | Client satisfaction (Z4) | 3.32 | 3.777 | 0.000 |
| Relationships between clients and contractors | Relationship at the start (Y1a) | 4.09 | 8.819 | 0.000 |
| | Relationship during project (Y2a) | 3.58 | 5.587 | 0.000 |
| | Relationship at the end (Y3a) | 3.66 | 5.738 | 0.000 |
| | Interpersonal relationship (Y4a) | 3.48 | 4.130 | 0.000 |
| Relationships between clients and consultants | Relationship at the start (Y1b) | 3.78 | 6.969 | 0.000 |
| | Relationship during project (Y2b) | 3.58 | 5.587 | 0.000 |
| | Relationship at the end (Y3b) | 3.65 | 5.240 | 0.000 |
| | Interpersonal relationship (Y4b) | 3.50 | 4.625 | 0.000 |

| Variables | | Mean | T Value | Sig. |
|---|---|---|---|---|
| Relationships between contractors and consultants | Relationship at the start (Y1c) | 4.07 | 8.546 | 0.000 |
| | Relationship during project (Y2c) | 3.58 | 5.587 | 0.000 |
| | Relationship at the end (Y3c) | 3.68 | 5.943 | 0.000 |
| | Interpersonal relationship (Y4c) | 3.33 | 3.364 | 0.001 |

The second objective is to ascertain the level of relationships among contracting parties. Table 2 shows significantly good relationship among contracting parties at the start of the project (Y1a, Y1b and Y1c), indicating good prior relationships. Projects have significantly harmonious relationships during project implementation (Y2a, Y2b and Y2c), pointing to good on-going relationships. At the end of the project, there is also significantly good relationship (Y3a, Y3b and Y3c). Interpersonal relationships (Y4a, Y4b and Y4c) are also considered significantly good.

The last objective of this study is to examine the effects of relationships among contracting parties on project performance. Correlation analysis was conducted to identify associations between relationships (Y1 to Y4) and project outcomes (Z1 to Z4). The significant correlations are depicted in Figures 1 to 3.

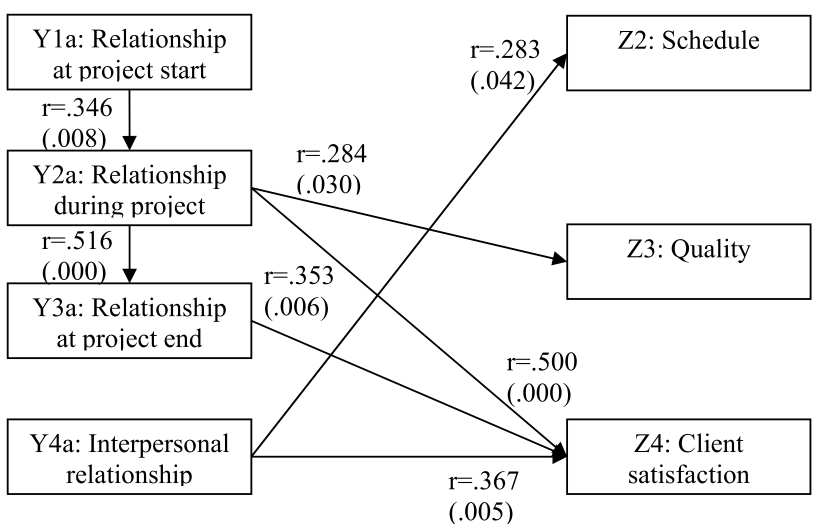


Figure 1: Effect of relationships between clients and contractors on project outcomes

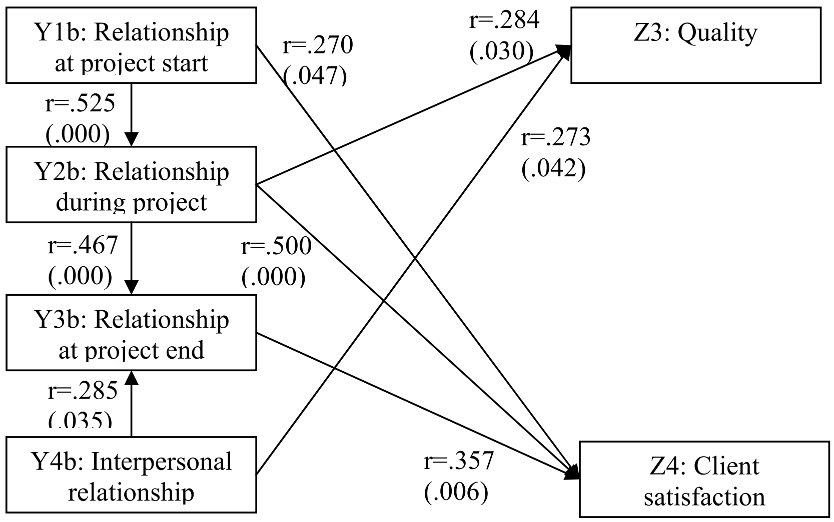


Figure 2: Effect of relationships between clients and consultants on project outcomes

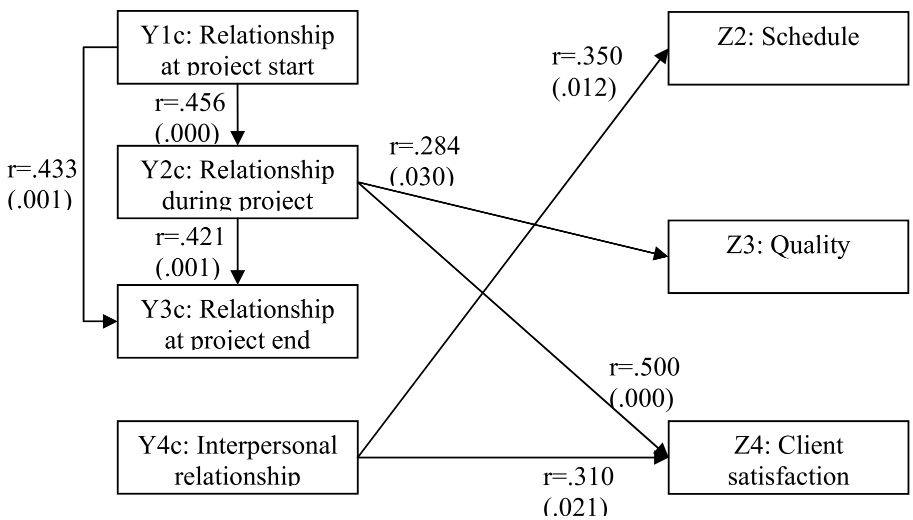


Figure 3: Effect of relationships between contractors and consultants on project outcomes

## DISCUSSION

Figures 1 to 3 show significant correlation between relationships among contracting parties at the start of the project (Y1) and level of harmony during project implementation (Y2). There is also significant correlation between harmony during project (Y2) and relationship at the end of the project (Y3). These suggest that with prior relationship, goodwill and loyalty have already been formed (Gulati, 1995). When contracting parties have worked with each other in previous projects, they have had the chance to interact, leading to cohesiveness (Walker and Guest, 1952), and are more comfortable around each other, leading to less anxiety and better understanding of each other's work (Katz, 1982).

Interpersonal relationships between clients and consultants (Y4b) are significantly correlated with relationships at the end of the project (Y3b). Significant correlation was also seen in relationships between contractors and consultants at the start (Y1c) and end (Y3c) of the project. Good prior and interpersonal relationships with consultants could engender good communication, thereby facilitate proper monitoring and timely feedback, and thus enhance relationships with consultants at the end (Jha and Iyer, 2006).

Significant correlation is observed between schedule performance (Z2) of public construction projects in Beijing with interpersonal relationships between clients and contractors (Y4a) and between contractors and consultants (Y4c). Contractors are usually pitted against clients and consultants, and may be regarded as adversaries (Yasamis et al., 2002). Good interpersonal relationships with contractors could enable better cooperation in monitoring construction activities more effectively. Instances of poor workmanship or improper usage of resources would also be reported promptly. These aid in completing the project on time (Dissanayaka and Kumaraswamy, 1999).

Quality performance of public construction projects (Z3) is significantly correlated with the harmony during the project (Y2) and the interpersonal relationship between clients and consultants (Y4b). The harmony during the project (Y2) would increase the interaction among project participants, improve mutual understanding and information sharing, and thereafter boost quality performance (Jha and Iyer, 2006). When trust and friendship are present in the good interpersonal relationship between clients and consultants (Y4b), consultants are more willing to work effectively and compromise when there are problems. Better quality could thus be achieved (Castro et al., 2009).

Figures 1 to 3 show that client satisfaction (Z4) is significantly correlated with the harmony during project (Y2), relationships between clients and consultants at the start (Y1b) and end (Y3b) of the project, relationships between clients and contractors at the end of the project (Y3a), and interpersonal relationships between clients and contractors (Y4a) and between contractors and consultants (Y4c). This agrees with Yasamis et al.'s (2002) finding that the level of client satisfaction could be determined by the transformation process from resources to the constructed facility. When the project process is harmonious (Y2), clients are likely to be satisfied. It is also understandable that the client satisfaction would exceed expectations, if clients have good relationships with contractors (Y3a) and consultants (Y3b). When selecting consultants, good prior relationships (Y1b) could be taken into account, because this reduces the risk of making mistakes in selection (Kubr, 1993). Due to prior relationships with clients, consultants may in turn work more effectively and hence achieve better client satisfaction. As explained above, good interpersonal relationships with contractors (Y4a and Y4c) could aid in completing the project on time and hence obtaining better client satisfaction.

## CONCLUSION

Using the questionnaire survey approach, this study investigated the effect of relationships among contracting parties on project performance in China's public construction projects. Data were collected from public owners and private contractors and consultants in Beijing. The data were analysed using correlation analysis and one-sample t test methods.

The results show that public construction projects in China had achieved significantly good quality performance and client satisfaction but not in budget nor schedule performance. The results also show that relationships among contracting parties play an important role in successful project outcomes. Schedule performance (Z2) is significantly correlated with interpersonal relationships between clients and contractors (Y4a) and between contractors and consultants (Y4c); quality performance (Z3) is significantly correlated with the project harmony level (Y2) and the interpersonal relationship between clients and consultants (Y4b); and client satisfaction is significantly correlated with the harmony during project (Y2), relationships between clients and consultants at the start (Y1b) and end (Y3b) of the project, relationships between clients and contractors at the end of the project (Y3a), and interpersonal relationships between clients and contractors (Y4a) and between contractors and consultants (Y4c).

The findings add to knowledge by showing that good relationships are important and may have an effect on performance of public projects in China. It is therefore important for public owners to consider prior relationships when selecting private partners. In addition, relationships should continue to be nurtured during project implementation as good on-going relationships affect project performance. Good relationships enable trust to be developed and firms can then opt for looser practices instead of cautious contracting, leading to good performance. It is therefore suggested that concerted effort should be taken to improve relationships in publically funded construction projects.

One limitation faced in this study is that Beijing may not truly represent China. This is because procurement arrangements for public works usually respond to local issues and constraints. The findings may not be easily generalized to other parts of China. Therefore the results should be interpreted carefully. In future studies, data from other cities such as Shanghai and Chongqing could be collected.

## ACKNOWLEDGEMENT

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# VALUE MANAGEMENT IN BUILDING CONSTRUCTION INDUSTRY OF NORTHERN CYPRUS: ADDRESSING A THEORY AND PRACTICE GAP

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## ABSTRACT

Construction sector in Northern Cyprus (TRNC) proved its potential of being locomotive in the economy after 2005. Increasing expectations to solve Cyprus problem, the positive reflections of the Annan Plan and the hypothetical abundance of liquidity in the world caused the construction sector to play the leading role in the economy of TRNC. However, these conditions have been reversed in a negative way today. Furthermore, internal problems such as high production costs, lack of international workshops, absence of development plan, lack of internationally certified construction firms, weak institutional and financial structure of contractors, low level of Value Management (VM) awareness among related authorities and private sectors, absence of country physical plan and less number of VM practitioners and consultants combined with uncontrollable external factors create negative impact on the sector's productivity and hence the competitiveness of the building industry.

The aim of this study is to review the gaps that exist, particularly on how VM is being practiced in to comparison with the published VM body of knowledge. Therefore, the unclear description of current applications and the level of VM practice in the country were investigated.

This research includes a comprehensive literature study, a structured questionnaire among construction management experts, interviews with building construction companies and related firms on the challenge of VM knowledge level and practice in building industry, analysis of this information to develop findings, and extending these to appraise the critical issues that could be targeted for building construction sector. The result of the survey, were further analyzed in details and guidelines were proposed to enhance an improved environment. Moreover, strategies were suggested to develop VM adoption and awareness level among construction industry practitioners in TRNC.
Keywords: Construction Industry, North Cyprus, Value Management.

## 1. INTRODUCTION

The concept of VM for the first time was introduced and developed by the purchase engineer of General Electric Company (GEC), Lawrence Miles in the 1940s. He proposed the value analysis method as an organized approach to providing the necessary functions at the lowest cost (Kelly et al., 2004).
Value management started its implementation in the mid-1980s as a value for money measure in construction industry of a number of countries. Kelly et al. (2004) stated that

"value management is the name given to a process in which the functional benefits of a project are made explicit and appraised consistent with a value system determined by the client, customer or other stakeholders". Value management is defined as a practical management style for augmenting value in projects. On the other hand, the concept of Value Engineering (VE) as a project management method, in terms of improving level of client satisfaction in projects, products, processes and systems, has been implemented for almost 60 years (Kelly et al., 2004).

Although VE is twice as old as VM, nowadays is placed as a sub-set of value management. This contradiction is illustrated as a sequential time-based phenomenon, whereby the VE and VM are considered simultaneously against the delivery process for a construction project (Figure 1). In fact, VM as a "soft system" is efficiently applied to appraise the matters of design/project objectives and their solutions. Generally VM approach is correlated with costumer or stakeholder fulfillment issues on early conceptual design phase or very beginning of the project. Practically, the VM approach is applicable through the entire project development (Bowen et al., 2010).

In addition, VE is presented as a "hard system" method in terms of cost reduction which is carried out during the design phase (where hard information in terms of technical solutions, drawings, specifications, etc. already exist) (Bowen et al., 2010).

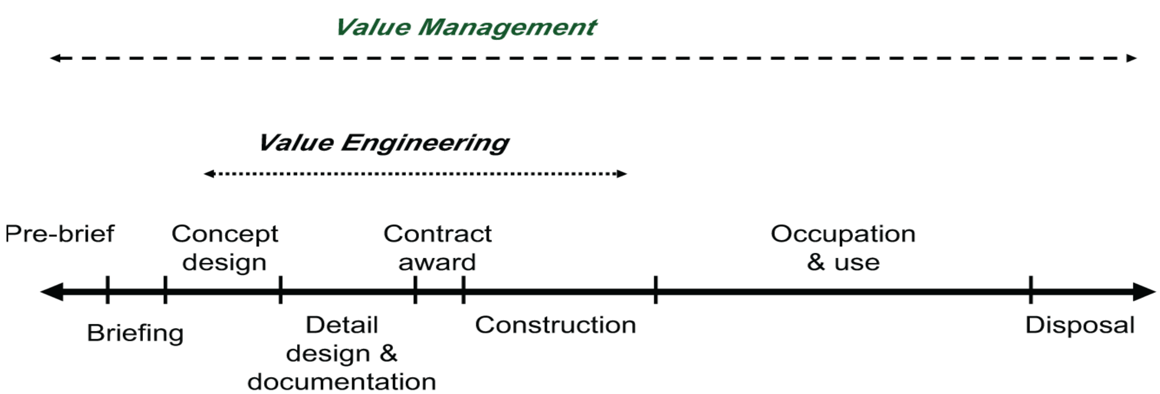


**Figure 1:** Building procurement process (Adopted from Bowen et al. (2010))

Value engineering, as a sub-set of Value management, has been implemented in the construction sector in last 30 years. Considerable research into the application of VM within the construction industry has been undertaken over the last three decades. The analysis of building components, best practice VM, and VM as a tool for project briefing and design process management are a few number of research studies in this matter.

Since there is no confidential scientific study on the awareness level, adoption terms and conditions of VM approaches in building industry of TRNC, this study is targeted to clarify this matter based on a pilot study as much as possible in this region. Initially, an investigation was attempted on building construction industry of North Cyprus. The aim was to reconsider the main critical matters and missing components in the construction sector. The literature study clarified that in addition to other lacks; application of VM was neglected or did not exist in the building construction sector which directly/indirectly has influenced the current critical condition of building construction industry of North Cyprus. Consequently, the correlation of customer or stakeholder with project at very beginning stage, creativity in problem solving approach, simultaneous consideration of concept and design in project brief, sufficient attention to functionality of building were also neglected.

In addition, it is tried to point out the interaction of the lack/week level of understanding of VM. Hence, costumer fulfillments, environmental impacts and construction market share circumstances based on the findings of exploration of VM through interviews and questionnaire were discussed. Finally, the possible strategies were suggested to develop VM adoption and awareness level among construction industry practitioners in TRNC.

## 2. LTERATURE REVIEW

### 2.1 Adoption of VM in Construction Industry

VM originally comes from the US manufacturing industry in 1940s. Since 1960s, the concept and application of VM is applied in the UK construction industry and structured gradually with a standard service, various tools, techniques and methodology. In addition, the techniques were spread to other countries such as; Australia, France Germany, India, Japan, Hong Kong, New Zealand, Malaysia and Saudi Arabia (Jaapar et. al, 2011).

VM implementation was introduced to construction industry of a number of countries as a value for money measure in the mid-1980s. The VM methods have been used and modified since its first introduction in the construction industry of USA. The first application of VM passed through US Congress and assigned to all governmental programs, projects, systems and products by budget of 80% of all governmental activities (Fong & Shen, 2000).

There are enormous studies, approaches and modifications on VM and the related issues since the global development of VM in 1960s. During the mid to late 1980s, a number of studies were conducted for the Royal Institution of Chartered Surveyors (RICS). The research outcomes were best practice for VM published in 1998 (Male et.al, 2007). In terms of the application of VM within the construction industry, a large number of studies like best practice VM; group dynamics in VM; adoption, inhibitors and success factors; VM and quantity surveying; the analysis of building components; VM as a tool for project briefing and design process management; the integration of risk and value management, performance measures, client value systems, and hard versus soft VM have been undertaken over the last three decades (Bowen et.al, 2010).

As an example of VM adoption in construction industry, the Construction Industry Development Board (CIDB) and the Economic Planning Unit (EPU) of Malaysia made special efforts in terms of VM practices to succeed more efficient value in their future public projects. A current research in Malaysian construction industry shows that implementation of VM circular on 71 public projects in Malaysia saved 23.53% of project total cost. Therefore, a guideline that entitled as "Value Management Guidelines Circular 3/2009" was published by EPU in December 2009 (Jaapar et al., 2011).

### 2.2 Practice of VM in Building Construction

A recent survey at the University of Cape Town was conducted on the awareness and understanding of VM among the quantity surveyors, engineers and architects of South Africa.

Precisely, the feedback of professional quantity surveyors showed there was less practice of VM in their organizations while they were generally aware of it. Also, it was indicated that their levels of awareness was more into the VE rather than the current development of VM. Therefore, the concept of VM is not understood and applied by quantity surveyors of South Africa in general (Bowen et al., 2010). Lately, an investigation on the understanding, practicing and implementation of VM in Malaysia has been undertaken. The research was structured on interviews, observations and literature study to identify the gaps on how VM is being practiced in the Malaysian construction industry. It was discovered that there is a gap between VM application approaches and how VM is currently being adopted. In addition, in terms of better value for money of governmental projects, it was recommended to consider VM application in all terms and conditions (Jaapar et al., 2011).

### 2.3 VM in Building Construction Industry of North Cyprus

Based on an investigation by World Health Forum, 18 countries are bordering the Mediterranean Sea with a population nearby 135 million. Cyprus is the third largest island in this coastal zone and located at 35$^{\circ}$N of the equator and 33$^{\circ}$E of Greenwich. The area of the North Cyprus is 3354 km² with population of about 300,000. The economy of this region is based on the service sectors including tourism and education, trade, the public sector, with smaller agriculture and light manufacturing sectors (AfsharGhotli & Celikag, 2009).

It should be indicated that the economy of North Cyprus is influenced by the existing political isolations. Although the size of the economy is followed by the size of the area, North Cyprus could reach to very high growth rates in the period of 2002 to 2007. Particularly, this achievement is caused by positive effect of efficient solutions to Cyprus problems. Therefore, the construction sector dominated the economy of the area via foreign demands. The very positive influences of building construction sector on the socio economic developments inspired a number of researchers to highlight the critical role of building construction sector in the North Cyprus (Şafakli, 2011). However, the wide range of effects and the interrelation of the construction sector with other sectors of the economy should be well known. As Şafakli (2011) stated in his research, occurrence of construction boom in North Cyprus caused critical matters on social costs, polluted environment and destroyed historical places.

The general performance factors of the building construction industry such as productivity, quality and product functionality are in lower rates in comparison to other industries. Yitmen (2005) addressed some key issues which North Cyprus is facing in its building construction industry. These matters were highlighted matters as revaluing the construction industry based on global competitiveness, organizational culture and change, usage of IT, performance measures and benchmarking for continuous improvement, best practices for constructability, and sustainable development.

“Just like the other countries in the region, Northern Cyprus is also faced with the problems of managing waste material” (AfsharGhotli & Celikag, 2009). The total waste generated in North Cyprus is directly linked to insignificant leach-ability and pollution content that caused by construction and demolition (C&D) waste materials. The amount of total generated waste caused by C&D activities in this Island were pointed out in the Master Plan of Solid Waste Management in the Turkish Cypriot Community as 45 percent per capita annually (AfsharGhotli & Celikag, 2010).

Turkish Contractors Association noted that, the numbers of contractors are increased from 171 in 2003 to 378 in 2008. Şafakli (2011) indicated that out of total construction projects, residential construction had 68.4% share in 2007 and 71.1% in 2008. Likewise, total construction value allocated to building was increased from 71.5% in 2007 to 83.2% in 2008 (Şafakli, 2011). Considerably, the growth constant of the construction sector affected by foreign demand from 2006 and reached to -8.0 % in 2008 (Table 1). It should be emphasized that social costs, polluted environment and serious damages on historical places were formed through this construction boom in North Cyprus. Likewise, the share of this sector in GDP was increased from 5.4% in 2002 to 7.9% in 2006 (Şafakli, 2011).

**Table 1:** Overview of the construction sector in North Cyprus economy (Şafakli, 2011)

| Variable | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|---|---|---|
| **GDP(€mlns)** | 43.4 | 55.0 | 60.2 | 98.3 | 174.4 | 204.1 | 190.8 |
| **Growth constant (%)** | 15.9 | 30.8 | 5.3 | 18.9 | 68.1 | 4.2 | **-8.0** |
| **GDP contribution (%)** | **4.4** | 5.0 | 4.3 | 5.4 | 7.9 | 7.9 | **7.1** |
| **Labor force (000"s)** | N.A | N.A | 8.1 | 8.2 | 9.6 | 9.7 | 10.5 |
| **Productivity (€)** | N.A | N.A | 7,432 | 11,987 | 18,166 | 21,041 | 18,171 |

The aforementioned characteristics of building construction industry of North Cyprus are clear enough to prove the critical condition of this sector. The improper building construction growth, economic fluctuations, instability in supply and demand of the construction sector, amount of generated waste (out of building construction, maintenance and demolition phases), and isolated economy are sufficient reasons to reevaluating this sector. However in this process, it should be considered that the building construction of North Cyprus "does not have any proactive strategy shaped by relevant vision, mission and objectives" (Şafakli, 2011).

## 3. RESEARCH METHODOLOGY

A comprehensive literature review, a structured questionnaire survey among construction management experts, interviews with building construction companies and related firms on the challenge of VM knowledge level and practice in building industry were adopted. Interviews were formed with most involved and largest construction companies of North Cyprus. Construction managers, design experts and directors of these companies were interviewed. Among almost 200 registered construction companies in the region, 25 were selected to be surveyed. The reason of selecting a sample size of 25 out of 200 was their annual widest building construction activities in whole country. Indeed, the aim of this investigation within the sample size was targeted to interview all 25 largest companies. Due to some restrictions and unavailability of the responsible persons, 10 companies (40%) were interviewed and other 8 companies just filed up the questionnaires.

Initially, the important factors of VM were asked to get a feedback on general knowledge of the target organizations. A rough and brief clarification of VM approach was followed by the VM important factors. The attempted technique was to illustrate a clear explanation on VM and its structured factors for the companies. It was assumed that possibly the organizations in building construction industry of North Cyprus are partially or fully dealing with VM methodology in their projects without knowing the nature and significances of the method. The questionnaires and interviews were designed based on VM indication factors in four separate sections as: (a) demographic information, (b) awareness of value management, (c) use of value management, and (d) nature and functionality of value management.

The findings and the collected data from questionnaire survey were summarized by SPSS application. In addition the interviews were recorded and scripted. Then understanding the conceptual relationships were applied by analyzing the keywords. The achieved feedbacks from interview approach were categorized, finalized and compared to the structured VM indicator factors of questionnaire. The interview provided opportunity of creating a sufficient atmosphere to open up the VM discourse in more details in order to gain different perspectives, comments and opinions. Consequently, the acquired records of interviews were compared to the findings of questionnaire.

## 4. FINDINGS AND DISCUSSION

### 4.1Findings

The feedbacks of interviews were obtained from the above 4 separate sections. It should be noted that these feedbacks mostly comes from the companies in field of construction and design with turnover about $ 1.6 M annually. Initially, a brainstorm on major factors of VM was delivered. As a result, the majority introduced and expressed on special attention to the relation between concept and design in the project brief as an important major factor. In addition, it has been pointed out, a clear vision and creative technique to solve problems of building construction projects is highlighted as another effective factor. It should be considered that none of the participant companies has membership of any professional VM institute.

In terms of lack/weak awareness level of VM, the main reasons were announced as; low number practitioners and missing of the authorized parties to provide and implementing of VM restriction in their building industry sector. Therefore, missing of the authorized parties to provide and implementing of VM restriction were underlined as the most effective and important reasons. In despite of that, a great number of the participants individually started to apply the VM approach to their organization in last 5 years. The most common VM method currently used among the building construction related companies of North Cyprus was clarified as “Job Plan”. The subsequences of VM application achievement were discussed with interviewed companies. Based on the results, optimization of value over the lifecycle of the project and time improvement was rated as highest items among their presented formal goals such as; lower environmental impact, enhanced functionality and lower cost.

The majority of the interviewed companies stated, the VM method as a tool can have the most influential positive effect on briefing and design phases in building construction projects. Moreover, in order to achieve project success, the most important factors like; time goals, customer fulfillment, operational and technical demands should be highly satisfied. The second priority presented as; budget goals and creating a new market through commercial success and producing larger building construction market share.

The starting point was investigating the major factors of VM within the sample population through questionnaire. As a result, a considerable response (23%) was on specific methodology based upon a creative problem solving approach in building construction project and preparing project brief by considering concept and design options.

**Table 2:** Considering major factors in VM approach (SPSS result)

| Major factors of VM | Responses |
|---|---|
| A specific methodology based upon a creative problem solving approach within your building construction project | 23.1% |
| Involving key stakeholders in a managed team approach within your building construction project | 15.4% |
| Focuses on function i.e. what it must do, not what it is within your building construction project | 15.4% |
| Focus on achieving value-added solutions based upon integration within your building construction project | 3.8% |
| Focus on project learning within your building construction project | 19.2% |
| Preparing project brief, and considering concept and design options within your building construction project | 23.1% |

In section A - demographic information- identified almost 43 % of the participants belonged to the building construction and design companies.

**Table 3:** Specification of organization specialty field (SPSS result)

| Organization activity fields | | Percent |
|---|---|---|
| **Activities** | Building construction contractor | 14.3% |
| | Building construction and design company | 42.9% |
| | Building construction and design consultant | 14.2% |
| | Building design consultant | 28.6% |

The surveyed companies had an annual turnover of above 3,000,000 Turkish Lira while none of them is a member of any professional VM institute (i.e. IVM, SAVE). The rate of VM awareness/lack of awareness among the selected companies before presenting them the majors and rough explanation of the method at very beginning of the investigation was studied in section B. The responds to the VM awareness in this section of the questionnaire shows that, only 30% of the companies were not familiar with any VM method. Indeed, missing specific restrictions was rated as the most important issue (50%) among the surveyed reasons of lack/weak level of VM awareness. Almost 60% of the remaining 70% knew some concepts of VM approach via an academic establishment or from attended courses. The ones not familiar with the method expressed their reasons as; unavailability of experts in the company, inefficient act form responsible authorities and no specific related restrictions in the entire country. In section C, the use of VM was studied and only 57% of the involved companies with the VM method had opportunity to implement the approach in their projects. Also, the highest rate (75%) of this implementation was recorded since 2009.

In section D where nature of VM application was studied, the advantages rate of considering VM as a tool/methodology in projects was 67%. The investigation stated the VM approach is mostly supported and applied by project engineer as an internal resource. Consequently, 50% believed that there was 11-15% cost saving and 33% rated on 21-25% improvement in functionality or performance of their organization. The respond to team dynamics factors on the successful operation of VM studies in organization is highlighted in Table 4 with the ratings of completely unimportant (1) up to extremely important (5).

**Table 4:** Team Dynamics factors on the successful operation of VM studies (SPSS result)

| Team Dynamics Factor | Extremely imp. (%) | Moderately imp. (%) | Relatively unimp. (%) | Very imp. (%) | Completely unimp. (%) |
|---|---|---|---|---|---|
| | 5 | 4 | 3 | 2 | 1 |
| **Team Size** | 33.3 | 33.3 | - | 16.7 | 16.7 |
| **Definition of Roles and Responsibilities** | 33.3 | 50.0 | 16.7 | - | - |
| **Team Composition** | 20.0 | 20.0 | - | 20.0 | 40.0 |
| **Formal and Informal Leadership** | 50 | 50 | - | - | - |
| **Team Cohesion** | 33.3 | 50 | 16.7 | - | - |
| **Group Goals/Goal-setting** | 50 | 33.3 | 16.7 | | |
| **Physical workshop location** | 16.7 | 66.6 | - | - | 16.7 |
| **Choice of External VM team versus Internal VM Team** | 50 | 16.7 | 33.3 | - | - |

Based on experience and responds of experts in the section (50%), VM and risk are generally managed together. Correspondingly, VM is mostly integrated with the company quality system (almost 67% of the responses). The reply to the question that to what extent is VM used as a tool in the project phases is illustrated in Table 5.

**Table 5:** To what extent is VM used as a tool in the project phases (SPSS result)

| Phases | Always (%) | Frequently (%) | Occasionally (%) | Seldom (%) | Never |
|---|---|---|---|---|---|
| **Briefing** | 50 | 33.3 | 16.7 | - | - |
| **Design** | 50 | 50 | - | - | - |
| **Planning** | 50 | 50 | - | - | - |
| **Production** | 50 | 50 | - | - | - |

Finally the interrelated important factors of VM and building construction project as product success were measured. As a result, meeting budget goals, meeting technical specifications and level of customer satisfaction placed as extremely important factors with 66.7% responds. Other most highlighted terms like; solving major operational problems and developing a new technology were rated as; 60% and 50% respectively.

## 4.2 DISCUSSIONS

Literature and feedbacks based on interviews and structured questionnaire on VM in building construction industry of North Cyprus were analyzed. The feedback of preliminary question proved that the survey population was inadvertently considering the major factors of VM. Likewise, the majority were working in building construction and design field with above $1.6 M annual turnover. Although the majority of the companies were considering the concepts of VM, this approach has not yet been applied properly. It was noticed that the achieved awareness which was only through the academic establishment or short courses were not efficient enough. In addition, dealing with VM academic theories without considering the real project circumstances could not be sufficient. Other important issues that should be discussed are lack of specific restrictions, unavailability of experts as in-house VM practitioners or external experts and very weak act form responsible authorities. As a result, the involved companies with the VM method had opportunity to implement the approach on few of their projects in the last 5 years. Although the large numbers of the selected companies are applying VM method from the quantitative point of view, still the quality control of the applied VM and common specific legislation on the projects is missed. Consequently, internal resources are acting as supporting sector of VM instead of external experts such as VM consultants, professional supervisors and official authorized parties. Although different VM methods exist globally, but the most common VM method currently used among the building construction industry of North Cyprus is clarified as "Job Plan". By considering the building market characteristics, Cypriot culture, available professional skills, economic growth, foreign demand and construction market share, other VM methods should be studied to apply the most efficient one.

Since time improvement and optimization of value over the full lifecycle of the projects were the most replied important VM goals within companies, the current condition of the projects were investigated respectively. The feedback from literature highlighted the important and critical issues of the construction sector in North Cyprus. For instance, it is noted that a considerable decrease (-8%) in the growth constant of the construction sector in 2008 and other critical problems were arisen due to the construction boom. Also, the productivity, quality and project functionality terms in the construction sector are standing in lower rates among the other industries. In addition, the huge amount of C&D wastes, increase in construction sites and current fluctuations on GDP by the construction sector in recent years and previous mentioned matters are enough reasons to claim that the building construction industry of North Cyprus is in an urgent need of appropriate solution.

Although there are advantages and disadvantages observed in recent years in the sector, an appropriate act to apply and supervise VM approach is suggested. Therefore, the first priority is considered to be awareness of the public, professionals and related sectors. In addition, using technical articles for interrelated new approaches, providing regulatory guidelines, academic seminars and technical short courses for this sector are recommended. In terms of proper use of the method providing new organization charts by including VM experts, specification enforcement, assigning authorized professional parties, commitment and involvement of government and chamber of engineers are proposed.

It is stated in the literature review that the VM process covers the whole lifecycle of the project. Therefore, customer satisfaction through clarification of demands could be more possible via proposed different alternatives and estimated costs. In addition, any further issues like building extension, maintenance throughout building lifecycle and changing the building functionality will be minimized. Also, proposed alternatives are provided by VM experts in order to satisfy proportionally the customer requirements, cost, quality and possibly environmental issues. Consequently, by taking special care on the method and implementation of its circumstances during given period the below given advantages will be obtained:

- Satisfaction and fulfillment of customer demands,
- Decrease in project (C&D) generated waste,
- Less fluctuation on construction market share,
- Suitable allocated value to buildings,
- Balance between supply and demand (local/foreign),
- Less building lifecycle maintenance cost, and
- Decreasing additional cost on society caused by environmental impacts and historical damages.

# 5. CONCLUSIONS

The challenge of VM knowledge and practice in building construction sector of the North Cyprus, through a number interviews and structured questionnaire among construction management experts and related firms were studied. Also, the advantages of VM method implementation, the critical reasons to highlight lack of awareness, the positive effects of the approach to the costumer and the environment were clarified. Therefore, to overcome the existing critical matters and achieve controllable construction sector productivity based on enhancing VM practice, some strategies were suggested. The main strategies include defining new organization charts by including VM experts, enforcement of specifications, assigning authorized professional parties, government involvement, notifying the public and professionals, using technical articles for interrelated new approaches, arranging academic seminars to fulfill the entire related VM shortage of building construction industry in North Cyprus. To sum up, the construction sector in the region is recommended to take a step towards implementation of the VM application. Consequently, the steps which should be taken by the sector experts and related parties through the previously suggested strategies could be highlighted as; to get to understand and improve the VM knowledge, modifying the organizations of the sector through the current practiced VM body of knowledge in the world, practicing on adoption of VM approach in the whole sector as an essential and finally attempt to develop a possible controllable VM association for the building construction industry of North Cyprus.

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# AN ANALYSIS OF CAUSES OF DISPUTES IN THE CONSTRUCTION INDUSTRY USING ANALYTICAL HIERARCHY PROCESS (AHP)

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**Abstract**

In the construction industry, since differences in perceptions among the participants of the projects, conflicts are inevitable. If conflicts are not well managed, they are quickly turn into disputes. Disputes are one of the main factors which prevent the successfully completion of the construction project. Thus, it is important to be aware of the causes of disputes in order to complete the construction project in the desired time, budget and quality.

This paper aims to analyze the main causes of disputes which occur in the construction industry. In order to reach this aim, a literature review was undertaken to identify the common construction disputes. The disputes derived from a cross-section of the literature, were classified into main categories and the main causes of construction disputes were determined. Finally, an analysis was carried out using the analytical hierarchy process (AHP) approach to determine their relative importance.

**Keywords:** Analytical Hierarchy Process (AHP), Causes of Disputes, Construction Disputes, Construction Management.

## INTRODUCTION

The construction industry is a complex and competitive environment in which participants with different views, talents and levels of knowledge of the construction process work together. In this complex environment, participants from various professions, each has its own goals and each expects to make the most of its own benefits. The increase in the number of participants of different cultural background in the construction value chain means more business interactions and arguments, whether contractual or social, resulting in an increase in the number of construction disputes (Kumaraswamy and Yogeswaran, 1998).

There are confusion among construction professionals about the differences between conflict and dispute, and these terms have been used interchangeably especially in the construction industry (Acharya et al., 2006). However, according to Fenn et al. (1997) conflict and dispute are two distinct notations. Conflict exists wherever there is incompatibility of interest. Conflict can be managed, possibly to the extent of preventing a dispute resulting from the conflict. On the other hand, disputes are one of the main factors which prevent the successfully completion of the construction project. Disputes are associated with distinct justiciable issues and require resolution such as mediation, negotiation arbitration, etc.

This paper aims to analyze the main causes of disputes which occur in the construction industry. In order to reach this aim, a literature review was undertaken to identify the common construction disputes. The main causes of construction disputes were determined by the help of the literature review. The disputes derived from the literature, were classified into main categories and their sub categories. Finally, an analysis was carried out using the analytical hierarchy process (AHP) approach to determine their relative importance.

## CAUSES OF DISPUTES IN THE CONSTRUCTION INDUSTRY

There has been considerable research undertaken to determine the causes of disputes in the construction industry. A literature review has been conducted in order to overview the causes of construction disputes. Table 1 summarizes the causes of disputes which are determined by several researchers from different countries.

Table 1: Causes of disputes in the construction industry (adapted from Kumaraswamy, 1997)

| Researches | Context | Causes of Disputes |
|---|---|---|
| Diekmann and Nelson (1985) | USA | (1) design errors, (2) discretionary or mandatory changes, (3) differing site conditions, (4) weather, (5) strikes and (6) value engineering |
| Hewit (1991) | General | (1) change of scope, (2) changed conditions, (3) delay, (4) disruption, (5) acceleration and (6) termination |
| Watts and Scrivener (1992) | Australia | (1) variations, (2) negligence in tort, (3) damages and (4) delays |
| Spittler and Jentzen (1992) | General | (1) ambiguous contract documents, (2) competitive / adversarial attitude and (3) dissimilar perceptions of fairness by the participants |
| Diekmann et al. (1994) | General | (1) people, (2) process and (3) product |
| Heath et al. (1994) | UK | (1) contract terms, (2) payments, (3) variations, (4) extensions of time, (5) nomination, (6) re-nomination and (7) availability of information |
| Rhys Jones (1994) | General | (1) poor management, (2) adversarial culture, (3) poor communications, (4) inadequate design, (5) economic environment, (6) unrealistic tendering, (7) influence of lawyers, (8) unrealistic client expectations, (9) inadequate contract drafting and (10) poor workmanship |
| Semple et al. (1994) | Canada | (1) acceleration, (2) restricted access, (3) weather and (4) increase in scope |
| Bristow and Vasilopoulous (1995) | Canada | (1) unrealistic expectations by the parties, (2) ambiguous contract documents, (3) poor communications between project participants, (4) lack of team spirit among participants and (5) a failure of participants to deal promptly with changes and unexpected conditions |
| Conlin et al. (1996) | UK | (1) payment and budget, (2) performance, (3) delay and time, (5) negligence, (6) quality and (7) administration |
| Sykes (1996) | General | (1) misunderstandings and (2) unpredictability |
| Kumaraswamy (1997) | Hong Kong | (1) variations due to site conditions, (2) variations due to client changes, (3) variations due to design errors, (4) unforeseen ground conditions, (5) ambiguities in contract documents, (6) variations due to external events, (7) interferences with utility lines, (8) exceptional inclement weather, (9) delayed design information and (10) delayed site possession |
| Yates (1998) | General | (1) variations, (2) ambiguities in contract documents, (3) inclement weather, (4) late issue of design information / drawings, (5) delayed possession of site, (6) delay by other contractors employed by the client and (7) postponement of part of the project |
| Al Momani (2000) | Jordan | (1) delays in payments to contractors and resulting cash problems during construction, (2) inferior quality of design, drawings and/or |

| | | |
|---|---|---|
| | | specifications, (3) stakeholders involved in the project, (4) variations initiated by the owner/consultant, (5) changed conditions and (6) weather |
| Mitropoulos and Howell (2001) | USA | (1) project uncertainty, (2) contractual problems, (3) opportunistic behavior, (4) contractor's financial position and (5) cost of conflict and culture |
| Brooker (2002) | General | (1) payment, (2) delay, (3) defect / quality and (4) professional negligence |
| Killian (2003) | USA | (1) project management procedure (change order, pre-award design review, pre-construction conference proceedings, and quality assurance), (2) design errors (errors in drawings and defective specifications), (3) contracting officer (knowledge of local statues, faulty negotiation procedure, scheduling, bid review contracting practices: contract familiarity/client contracting procedures), (4) site management (scheduling, project management procedures, quality control, and financial packages) and (5) bid development errors (estimating error) |
| Sheridan (2003) | General | (1) valuation of variations, (2) valuation of final account and (3) failure to comply with payment provisions |
| Fryer et al. (2004) | General | (1) inception/briefing/tendering, (2) design, (3) construction operations and (4) project management |
| Adriaanse (2005) | General | (1) material/workmanship quality, (2) delays, (3) variations, (4) cost increase and (5) different interpretations of the contract provisions |
| Ashworth (2005) | General | (1) general (contracts, communication, fragmented structure of the sector, tendering practices), (2) employer (scope, variations, changes made in standard contracts, interventions to the PM, payment delays), (3) consultants (design errors, inexperience, late/inadequate instructions, lack of coordination, inadequate responsibility descriptions), (4) contractors (insufficient site management, inadequate planning, quality, problems with subcontractors, delay in paying subcontractors, insufficient coordination of subcontractors), (5) subcontractors (failure to oblige by contractual requirements, quality) and (6)suppliers (low performance products) |
| Chan and Suen (2005) | China | (1) payments, (2) variations, (3) extension of time, (4) quality of works, (5) project scope definition, (6) risk allocation, (7) technical specifications, (8) management, (9) unrealistic client expectations, (10) availability of information, (11) unclear contractual terms, (12) unfamiliarity with local conditions, (13) difference in way of doing things, (14) poor communication, (15) adversarial approach in handling conflicts, (16) lack of team spirit, (17) previous working relationships, (18) lack of knowledge of local legal system, (19) conflict of laws and (20) jurisdictional problems |
| Cheung and Yiu (2006) | General | (1) task interdependency, (2) differentiations, (3) communication obstacles, (4) tensions, (5) personality traits, (6) non performance, (7) payment, (8) time and (9) contract provision |
| Waldron (2006) | Australia | (1) variations to scope, (2) contract interpretation, (3) EOT claims, (4) site conditions, (5) late, incomplete or substandard information, (6) obtaining approvals, (7) site access, (8) quality of design and (9) availability of resources |
| Abd El-Razek et al. (2007) | Egypt | (1) variations initiated by owner / consultant, (2) inferior quality of design, drawings and/or specifications and (3) delays of approval of shop drawings, instructions and decision making |
| Yiu and Cheung (2007) | General | (1) variation, (2) delay in work progress, (3) expectations and (5) inter parties' problems |
| Abeynayake (2008) | Sri Lanka | (1) breaches of contract by any party to the contract, (2) inadequate administration of responsibilities by the owner or contractor or sub contractors, (3) some plans and specifications that contain errors, omissions and ambiguities and (4) sudden tax and cost increase |
| Love et al. (2010) | Australia | (1) nature of the task being performed (failure to detect and correct |

| | | |
|---|---|---|
| | | errors), (2) people's deliberate practices (failure to oblige by contractual requirements) and (3) circumstances arising from the situation or environment the project was operating in (unforeseen scope changes) |
| Gad et al. (2011) | General | (1) different contractual factors, (2) cultural backgrounds, (3) legal and economic factors, (4) languages, (5) technical standards, (6) procedures, (7) currencies and (8) trade customs |
| Jaffar et al. (2011) | Malaysia | (1) behavioral problems (reluctant to check for constructability, clarity and completeness and poor communication among project team), (2) contractual problems (late giving of possession, delay interim payment from client and unclear of contractual terms) and (3) technical problems (contractor fails to proceed in a competent manner and late instructions from architect or engineer) |
| Ilter (2012) | Turkey | (1) variations, (2) late instructions by the employer, (3) inadequate/incomplete specifications, (4) unclear contractual terms, (5) adversarial approach in handling conflicts, (6) unclear scope definition, (7) poor communication, (8) unfamiliarity with local conditions and (9) technical inadequacy of the contractor |

As it is shown in Table 1, the causes of disputes are first examined and identified through a relevant literature review. Although researchers have concentrated on various causes of disputes, when the table is analyzed in detail, it can be seen that there is a certain level of commonality in the causes of disputes. In this context, it is necessary to classify the common causes of disputes into categories. The causes of disputes are classified into seven broad categories depending on their nature and mode of occurrence. As a result, 28 common causes of dispute are selected for further examination in this study (Table 2).

Table 2: Common causes of disputes by categories

| **Category of Disputes** | **Causes of Disputes** |
|---|---|
| **Owner related** | variations initiated by the owner |
| | change of scope |
| | late giving of possession |
| | acceleration |
| | unrealistic expectations |
| | payment delays |
| **Contractor related** | delays in work progress |
| | time extensions |
| | financial failure of the contractor |
| | technical inadequacy of the contractor |
| | tendering |
| | quality of works |
| **Design related** | design errors |
| | inadequate / incomplete specifications |
| | quality of design |
| | availability of information |
| **Contract related** | ambiguities in contract documents |
| | different interpretations of the contract provisions |
| | risk allocation |
| | other contractual problems |
| **Human behavior related** | adversarial / controversial culture |
| | lack of communication |
| | lack of team spirit |
| **Project related** | site conditions |
| | unforeseen changes |
| **External factors** | weather |
| | legal and economic factors |

| | |
|---|---|
| | fragmented structure of the sector |

The data in Table 2 is used in the process of analytical hierarchy process (AHP) approach for determining disputes' relative importance.

## THE ANALYTICAL HIERARCHY PROCESS

The analytical hierarchy process (AHP) developed by Saaty (1980) is a strong and flexible multi-criteria decision analysis approach. In this approach, the most important steps are formulating the decision problem and constructing the hierarchy. After constructing the hierarchy, the decision maker can begin to prioritize the factors in order to determine the relative importance of them in each level of the hierarchy. Factors in each level are pair-wise compared with respect to their importance. pair-wise comparison is based on a scale of 1 to 9 as per the definition of weights given in Table 3. Pair-wise comparison makes the decision maker to compare each factor with all the remaining ones.

Table 3: AHP pair-wise comparison matrix for procurement selection criteria (Saaty, 1980)

| **Intensity of importance** | **Definition** | **Explanation** |
|---|---|---|
| 1 | Equal importance | Two criteria are of equal importance |
| 3 | Weak importance of one over another | Experience and judgment slightly favor one criterion over another |
| 5 | Essential and strong importance | Experience and judgment strongly favor one criterion over another |
| 7 | Very strong and demonstrated importance | A criterion is strongly more important than the other |
| 9 | Absolute importance | The evidence favoring one criterion over another is of the highest possible order of affirmation |
| 2, 4, 6, 8 | Intermediate values between adjacent scale values | When compromise is needed |
| Reciprocals of above nonzero | If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i | A reasonable assumption |

In this paper, Super Decisions software program is used in order to identify the relative importance of causes of disputes. In Super Decisions, the decision-maker first structures the problem into different hierarchical levels. The model is built from the top starting with the main dispute causes, then the more specific (sub-categories) ones. Seven main dispute causes are included in the first level of hierarchy and 28 sub dispute causes in the second level, as shown in Table 2. Once the hierarchy structure is established, the decision-making process can take place. The decision-maker derives ratio-scale (as shown in Table 3) priorities reflecting the relative importance of dispute causes via pair-wise comparisons.

The pair-wise comparisons are done with respect to overall goal of the model: analyzing main causes of construction disputes. Table 4 shows an example for contract related dispute causes, their comparison values and relative importance values. The decision-maker, in this particular example in Table 4, assigned the "ambiguities in contract documents" a weight of 4 compared with the "different interpretations of the contract provisions". Thus, the decision-maker considers the "ambiguities in contract documents" to be moderately more important than the "different interpretations of the contract provisions" as a dispute causes. From this matrix, the normalized relative importance values of the four contract related dispute causes can be computed. The relative importance values are also shown in the last column of Table 4.

Table 4: Pair-wise comparison for the contract related dispute factors

| | ambiguities in contract documents | different interpretations of the contractprovisions | risk allocation | other contractual problems | relative importance |
|---|---|---|---|---|---|
| ambiguities in contract documents | 1 | 4 | 5 | 7 | 0.2729 |
| different interpretations of the contractprovisions | 1/4 | 1 | 4 | 7 | 0.1276 |
| risk allocation | 1/5 | 1/4 | 1 | 6 | 0.0589 |
| other contractual problems | 1/7 | 1/7 | 1/6 | 1 | 0.0194 |

All main dispute categories, their sub-categories and their relative importance values are presented in Table 5.

Table 5: Relative importance of disputes causes by categories

<table>
<tr><th>Main Categories</th><th>Relative importance of main categories</th><th>Sub-categories</th><th>Relative importance of sub-categories</th></tr>
<tr><td rowspan="6">Owner related</td><td rowspan="6">0.1993</td><td>variations initiated by the owner</td><td>0.0449</td></tr>
<tr><td>change of scope</td><td>0.0415</td></tr>
<tr><td>late giving of possession</td><td>0.0111</td></tr>
<tr><td>acceleration</td><td>0.0049</td></tr>
<tr><td>unrealistic expectations</td><td>0.0110</td></tr>
<tr><td>payment delays</td><td>0.0859</td></tr>
<tr><td rowspan="6">Contractor related</td><td rowspan="6">0.0916</td><td>delays in work progress</td><td>0.0329</td></tr>
<tr><td>time extensions</td><td>0.0329</td></tr>
<tr><td>financial failure of the contractor</td><td>0.0037</td></tr>
<tr><td>technical inadequacy of the contractor</td><td>0.0049</td></tr>
<tr><td>tendering</td><td>0.0029</td></tr>
<tr><td>quality of works</td><td>0.0142</td></tr>
<tr><td rowspan="4">Design related</td><td rowspan="4">0.1364</td><td>design errors</td><td>0.0287</td></tr>
<tr><td>inadequate / incomplete specifications</td><td>0.0501</td></tr>
<tr><td>quality of design</td><td>0.0501</td></tr>
<tr><td>availability of information</td><td>0.0074</td></tr>
<tr><td rowspan="4">Contract related</td><td rowspan="4">0.4789</td><td>ambiguities in contract documents</td><td>0.2729</td></tr>
<tr><td>different interpretations of the contract provisions</td><td>0.1276</td></tr>
<tr><td>risk allocation</td><td>0.0589</td></tr>
<tr><td>other contractual problems</td><td>0.0194</td></tr>
<tr><td rowspan="3">Human behavior related</td><td rowspan="3">0.0263</td><td>adversarial / controversial culture</td><td>0.0027</td></tr>
<tr><td>lack of communication</td><td>0.0191</td></tr>
<tr><td>lack of team spirit</td><td>0.0045</td></tr>
<tr><td rowspan="2">Project related</td><td rowspan="2">0.0518</td><td>site conditions</td><td>0.0259</td></tr>
<tr><td>unforeseen changes</td><td>0.0259</td></tr>
<tr><td>External factors</td><td>0.0156</td><td>weather</td><td>0.0071</td></tr>
</table>

| | | | |
|---|---|---|---|
| | | legal and economic factors | 0.0071 |
| | | fragmented structure of the sector | 0.0014 |

As it is shown in Table 5, "contract related disputes" has the highest relative importance value with the value of 0.4789. In other words, "contract related disputes" are the common ones in the construction industry. In this study, contract related disputes consist four different sub-disputes causes. These sub-dispute causes and their relative importance values are: ambiguities in contract documents (0.2729), different interpretations of the contract provisions (0.1276), risk allocation (0.0589), other contractual problems (0.0194). When all sub-dispute causes evaluated together, it can also be seen that, "ambiguities in contract documents" has the highest relative importance with the value of 0,2729. In other words, "ambiguities in contract documents" is an important dispute cause in the construction industry. Other common dispute causes are "different interpretations of the contract provisions", "payment delays", "risk allocation", "inadequate / incomplete specifications" and "quality of design" all with relative importance values higher than 0.050. On the other hand, human behavior related dispute causes and external factors are the least common dispute causes with the relative importance value of 0.0263 and 0,0156 respectively.

## CONCLUSION

In this paper, the main causes of dispute causes in the construction industry were analyzed. First of all, the main causes of construction disputes were determined with a comprehensive literature review. Then, the disputes derived from the literature, were classified into main categories. According to the classification, main disputes categories were found as; owner related disputes, contractor related disputes, design related disputes, contract related disputes, human behavior related disputes, project related disputes and external factors. All these disputes categories have their own sub-dispute causes. After determining the dispute causes, an approach was carried out using the AHP and an AHP model was developed. The model considers the relevant dispute causes which occur in the construction projects. Finally, an analysis was carried out to identify the relative importance of the different dispute causes. The analysis reveals that the contractor related disputes and their sub-dispute categories are the most common ones in the construction industry.

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# IMPROVING CAMPUS CHILLED WATER SYSTEMS WITH INTELLIGENT CONTROL VALVES: A FIELD STUDY

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## ABSTRACT

The degradation of the temperature difference between supply and return flow, known as ΔT degradation, in chilled water systems has been widely observed and documented over the last 25 years. High pumping energy consumption as well as reduced efficiency of the chillers operating under part-load conditions, lead to a decrease of overall system efficiency of chilled water plants. This article describes a field study conducted on two university campuses in Massachusetts and Colorado during the cooling season of 2011. The purpose of this experimental study was to alleviate ΔT degradation problems on both campuses through the use of intelligent pressure-independent control valves, and to quantify the improvements achieved. The MA field results revealed that the intelligent control valves when coupled with a ΔT management strategy have allowed the campus to serve additional cooling load on its campus with the same distribution and central plant system.

Keywords: chilled water plants; delta T degradation; energy efficiency; building retrofits;

## INTRODUCTION

The degradation of the temperature difference between supply and return flow, known as ΔT degradation, in *chilled water systems* has been widely observed and documented over the last 25 years. While commonly the problem of decreasing waterside temperature difference is reported, the real problem is the corresponding increase in water flow rate. Especially under part-load conditions, when the mass flow rate relative to the cooling load increases, an additional chiller and cooling tower need to be brought online to maintain the flow requirements even though the cooling capacity limits of the chillers have not yet been reached. Both, high pumping energy consumption as well as reduced efficiency of the chillers operating under part-load conditions, lead to a decrease of overall system efficiency of chilled water plants.

Common causes of low ΔT in chilled water plants include oversized control valves (leading to two-position behavior, valve hunting, and suboptimal use of flow), lack of hydraulic balancing, and fouled cooling coils (Taylor 2002). For illustration purposes, imagine a central chilled water plant equipped with two 200-ton chillers in parallel, each served by a dedicated chilled water pump controlled by a variable frequency drive. Assuming that the plant operates as designed at a 12°F (6.7K) ΔT between chilled water supply and return temperature, a load of 180 tons (633 kW), constituting a 45% plant part load, would lead to a 360 GPM (22.7 L/s) distribution loop flow and call for only one of the two chillers operating at 90% of its capacity, as shown in Figure 1 on the left. If, however, for reasons named above, the ΔT has degraded from 12°F to 10.4°F (5.8K), serving the same load of 180 tons (633 kW), would now require 414 GPM (26.1 L/s) of distribution loop flow, i.e., 15% more than in the case of as-designed operation, in response starting the second chiller and potentially another cooling tower based on flow demand, yet not in response to cooling demand since the load is still 180 tons. Each of the two chillers operate at a much lower part-load ratio of 45% with a loss in central plant efficiency associated with operating two chillers at low part-load rather than one chiller near capacity.

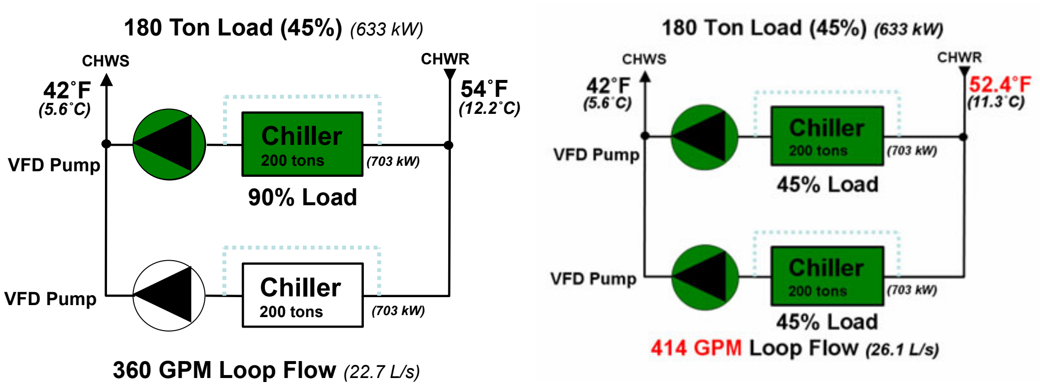



Figure 1: Central chilled water plant operating at design of 12°F (6.7K) (left) and degraded of 10.4°F (5.8K) (right)

Moreover, due to changes of technology in *central heating plants* such as condensing boilers and combined heat and power systems over the past 15 years, the problem of ΔT degradation has also been observed in many heating applications. Especially in large heating systems such as those used for district heating, the return water temperature has a significant influence on the overall system efficiency.

This article describes a field study conducted on the campuses of the Massachusetts Institute of Technology (MIT) and the University of Colorado Boulder (UCB) during the cooling season of 2011. The purpose of this experimental study was to alleviate ΔT degradation problems on both campuses through the use of advanced pressure-independent control valves, and to quantify the improvements achieved. The flow control devices deployed, five at MIT and six at UCB, are novel two-way exponential (equal-percentage) control valves mated with a magnetic flow meter, temperature sensors in both waterside supply and return lines, and several microprocessors, that can carry out a multitude of control strategies. The intelligent control valve has internet capabilities and different strategies can be downloaded remotely using internet and the built-in web server.

These novel control valves are independent of pressure fluctuations in the distribution loop as the flow through each coil is controlled directly by the control signal, rather than indirectly through a valve position. Should the upstream pressure change at a particular flow request, the microprocessor will adjust the valve position through a device-internal cascaded control loop. Conversely, a conventional pressure-dependent control valve would suffer a flow variation, which would first need to be detected by the coil control loop and then corrected thereafter. Moreover, by measuring flow and $\Delta T$ at the same time, waterside cooling loads can be calculated and a coil characteristic of load versus water flow be established over time, which may serve diagnostic purposes.

A novel feature of the installed valves, derived partially from Hartman (2000), is a strategy that combats low $\Delta T$, which is explained in greater detail in Figure 3 below: The primary $\Delta T$ logic loop is constantly monitoring the measured $\Delta T$ and compares it to the $\Delta T_{lim}$ setpoint. If $\Delta T$ is lower than its setpoint plus a hysteresis value, the $\Delta T$ logic calculates a new flow setpoint to maintain the desired $\Delta T_{lim}$ setpoint.

## LITERATURE REVIEW

Though increasingly variable primary systems are adopted, in many older facilities the design of large chilled water systems has been dominated by decoupling the primary chilled water plant flow from the secondary load side water flow by means of a bypass line. In addition, the load side distribution networks are frequently equipped with bypass lines on individual loads to avoid operating constant speed pumps against closed control valves. According to chiller manufacturers, in cooling systems, the primary/secondary design requiring constant flow in the primary loop was due to chiller control stability issues. Conversely, in central heating systems, the approach originates back to a high return temperature being required in order to avoid condensation in the boilers with associated corrosion damage. The load side bypass lines as well as the primary/secondary configuration in conjunction with constant speed pumps, lead to constant primary and secondary mass flow rates and to $\Delta T$ degradation under part-load conditions in both chilled water plants and central heating applications.

Particularly in older primary/secondary chilled water system configurations, the high distribution side mass flow rate, as a result of constant speed pumping, leads to high pumping energy consumption. Peyer and Bahnfleth (2006) showed that the additional amount of pump energy due to the excess primary flow associated with primary/secondary systems, while not huge, is significant. A secondary problem is the resultant difficulty in controlling the chillers, as additional chillers need to be brought online to maintain adequate flow requirements even though the cooling capacity limits of the chillers have not yet been reached. Both effects result in overall reduced system efficiency. For that reason, numerous investigators such as Reed (2007), Harrell (2009), Taylor (2006), and Ma (2010) propose several possibilities including bypass check valves, variable speed pumps, and variable flow primary loop to reduce bypass mass flow and increase efficiency. Taylor (2002) and Fiorino (1996) provide a comprehensive overview of the various possibilities to reduce the mass flow rates in hydraulic systems under typical operating conditions with the intention to increase the temperature difference between supply and return flow. Both authors mention that oscillation of control valves around their respective setpoints (e.g., due to oversized control valves) leads to a higher average mass flow rate than desired, and thus ΔT is degraded; however, the extent of ΔT degradation is not quantified.

In a study of a different campus, the University of California Riverside was experiencing many problems with their chilled water system, which resulted in a low waterside temperature differences and even negative differential pressure measurements at remote loads. Hyman and Little (2004) report that a 1°F (0.6K) drop in delta-T results in a 5% loss in capacity of the chilled water thermal energy storage system. As the campus grew, the existing thermal energy storage system could no longer offset the cooling demand.

Similarly, in large central heating systems, ΔT degradation plays an ever-increasing role. Floss (2006) points out that condensing boilers require a very low return water temperature to the boiler to achieve a significant condensing effect and the expected high efficiency. In practice, many combined heat and power plants go offline or initiate the emergency cooling when the return flow temperature exceeds 160°F (71°C). The causes for high return water temperatures in central heating systems are the same as low return water temperatures in chilled water systems: The mass flow is not adjusted downward as the loads drop, leading to excessive water flow rates and ΔT degradation.

For district heating systems, ΔT degradation has three efficiency detriments, which are higher pumping energy consumption, higher heat losses in the warm return pipes, and lower primary energy efficiency in heat and power generation. Moreover, the high mass flow rates at low ΔT limit the maximum heating capacity that can be provided by the district heating system, preventing the opportunity to grow the reach of the district heating network to new customers.

## COOLING COIL PERFORMANCE MODELING

A simulation tool was developed to generate performance maps based on established relationships for dry and wet cooling coils presented by McQuiston, Parker and Spitler (2005) in order to establish expected coil behavior for a range of operating conditions, before analyzing any operational data. Consider a cooling coil served with a variable chilled water flow of up to 6.3 L/s (100 GPM) at temperatures of either 5°C (design) or 9°C (far too warm). The entering mixed airflow of a constant 3,540 L/s (7,500 CFM) is at 28°C and either 40% (moderate) or 80% (high) relative humidity. Defining the normalized total (sensible and latent) coil load $q_{Tot}$ as the current load met at a particular chilled water flow to the total load achieved at maximum flow of 6.3 L/s and the normalized flow $\phi$ as the current flow to the maximum flow, one can develop characteristic coil maps for each of the entering water and air states as shown in the upper graph of Figure 2. In addition, in the lower graph one can see the development of the waterside ΔT [K]. The green lines refer to the more humid entering air state and the dashed lines depict the warmer entering water temperature. While the maximum total load for the cold supply water of 5°C and humid entering air of 28°C and 80% RH, at 161 kW is much higher than the 71 kW for warm chilled water and dryer entering air, nonetheless, the *normalized coil characteristic* remains nearly unchanged. At 40% normalized flow, 90% of the maximum total coil load is delivered. To deliver the next 6% of capacity, the flow must be doubled from $\phi$ =0.4 □□ 0.8, an effect of diminishing returns referred to as *saturation*. The intelligent control valve presented here is parameterized to reveal flow saturation that occurs for high values of normalized flow such as $\phi > 0.6$, i.e. here > 60 GPM by harnessing a model of the cooling coil being controlled that was calibrated during valve commissioning.

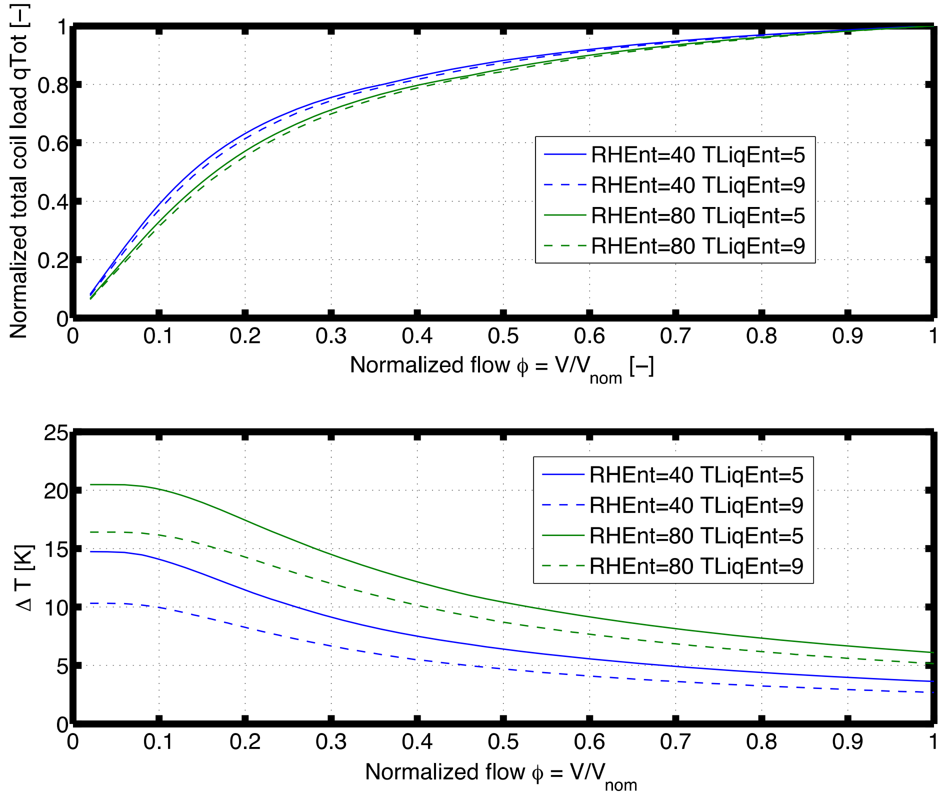



Figure 2: Coil Performance Map (top) and ΔT Development with Norm. Flow (bottom)

The careful reader will notice that limiting ΔT must be carefully deployed. Choosing for instance a low $\Delta T_{lim}$ of 6 K, limits the normalized flow to 55% and the coil total load to $q_{Tot}$=91% when the entering chilled water is at its design of 5°C and the entering air is at 40% RH. Under very humid entering air conditions, the same $\Delta T_{lim}$ leads to a much higher normalized flow of 95% and $q_{Tot}$=99%. In other words, a $\Delta T_{lim}$=6K allows the coil to deliver > 90% of its maximum capacity. Conversely, choosing a high $\Delta T_{lim}$ of 12 K, limits the normalized flow to 20% and the coil total load to $q_{Tot}$=65% when the entering chilled water is at its design of 5°C and the entering air is at 40% RH. Under very humid entering air conditions, the same $\Delta T_{lim}$ leads to a much higher normalized flow of 42% and $q_{Tot}$=80%. An engineering software tool was developed that analyzes coil operational data for several weeks to ensure that the $\Delta T_{lim}$ chosen is not too high so that the heat exchanger is always allowed to approach the saturation region, i.e. without excessively curtailing coil load delivered. For the Massachusetts campus field study, a $\Delta T_{lim}$ of 6.7 K (12°F) was chosen using said tool.

## DESCRIPTION OF CAMPUS CHILLED WATER SYSTEMS

In Massachusetts, the university campus central chilled water system consists of 30,400 tons (107 MW) of absorption and electric centrifugal chillers. An internal study conducted in 2008 showed a plant ΔT as low as 2°F (1.1K) with an average annual ΔT of approximately 6°F (3.3K). The study also estimated that annual savings of $1.5M would accrue if the average ΔT could be improved to 12°F (6.7K). One building with very low ΔT is the Hayden Library: This 1947 vintage building was built with its own chiller and later converted to campus district cooling. The air handler coils were designed in 1947 for a 6°F (3.3K) ΔT assuming 50°F (10°C) entering and 56°F (13.3°C) leaving temperature. However, today the plant is operating at 44°F (6.7°C) entering water temperature, offering the potential for much higher coil capacities and waterside ΔT, yet the building was operating at a ΔT of only 2 to 6°F (1.1 to 3.3K). A detailed description of the pilot projects undertaken in the building to increase ΔT is provided below.

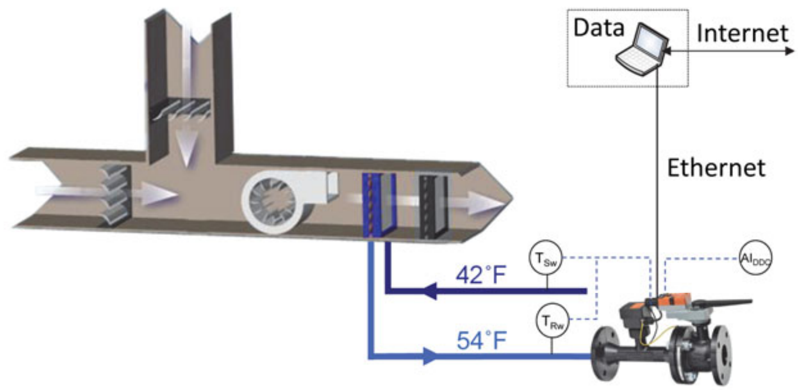
## DESCRIPTION OF RETROFIT PROJECT

The main library on the Massachusetts campus is a three-story 153,000 gross square foot (14,286 $m^2$) building constructed in 1947. In addition to a number of fan coils, the building is conditioned by six air handlers ranging in capacity from 7,500 to 30,000 cfm (3,540 to 14,160 L/s).

As mentioned above, the coil ΔT on most air handlers averaged 6°F (3.3K). The principal cause of the low ΔT was over-pumping of the coils. To improve this situation, two control strategies were tested in a pilot project. Initially, two air handlers were tested, one using a ΔT control strategy applied to a new motorized conventional, i.e. pressure dependent, globe valve that replaced a deteriorated existing one and the other using a pair of pressure independent ΔT control valves. Two tandem valves were used because the required flow rate for the coil exceeded the capacity of the (then available) pressure independent valves of that type. These valves were at that time not equipped with the flow meters that are part of the intelligent control valves today, but rather used a mechanical pressure independent mechanism. A new globe valve was installed so that a comparison between pressure independent and pressure dependent valves could be conducted. All three valves on the two air handlers used the same ΔT control strategy: Both approaches increased the ΔT of the air handlers to 12°F (6.7K) but the pressure independent arrangement gave better control as indicated by a smaller standard deviation of only 0.7°F (0.4K) as compared to a standard deviation of 1.5°F (0.8K) for the pressure dependent valve. The conclusion is that both the pressure independence *and* the ΔT management strategy were required to get the best and most consistent result.

As larger pressure independent valves with the ΔT strategy had become available in the meantime, the remaining four air handlers, along with the one that had used the new globe valve, were now retrofitted and tested with new intelligent control valves. Air handling unit AHU-5, equipped with the mechanically pressure independent valves and ΔT manager, was left in that configuration as the setup was performing well. Since this valve arrangement lacks the accurate flow measurement of the intelligent control valves (magnetic flow meter), it is excluded from the detailed data analysis.

A prototypical retrofit scenario is sketched in Figure 3, which shows the cooling coil in an air-handling unit, equipped with intelligent control valve that receives the analogue input signal from the building automation system just as any other control valve would. For the purpose of acquiring evidence on the performance of these valves in this experimental study only, each valve was connected to a dedicated laptop, data acquisition software, and a wireless Internet connection for remote monitoring and maintenance.



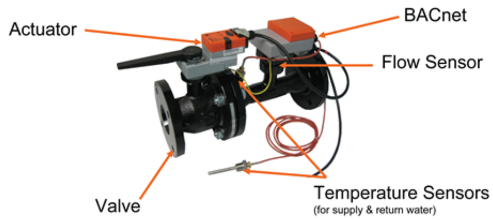




Figure 3: Case Study Experimental Setup (top) and Intelligent Control Valve (bottom)

## RESULTS

Figure 4 documents the findings for one of the Massachusetts library cooling coils, AHU-6, shown as a cooling power [Btu/h] vs. water flow rate [GPM] with the data being collected by the control valve itself, and not a separate data acquisition system. As flow increases from 0 to 60 GPM (0 to 3.8 L/s), cooling power increases from 0 to 300 kBtu/h (0 to 88 kW), yet a clearly exponentially decaying behavior can be observed: While the first 20 GPM (1.3 L/s) provide roughly 180 kBtu/h (53 kW), the last 20 GPM from 40 to 60 GPM (2.6 to 3.8 L/s) provide an incremental increase of less than 40 kBtu/h (12 kW). The waterside temperature difference, starting with roughly 25°F (14K) drops with increasing flow rate to 5°F (2.8K), in an approximately inverse trend to the cooling power. Both thermal power output and waterside temperature difference show the behaviour expected from the coil analysis shown in Figure 2.

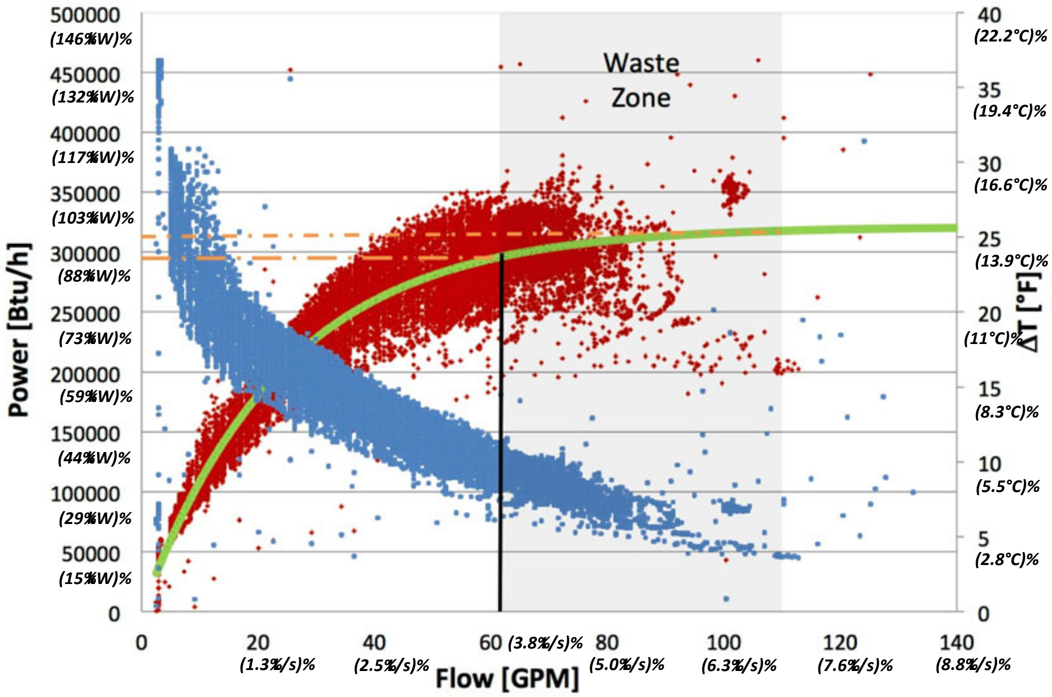



Figure 4: AHU-6 Cooling Coil Performance July 1-22, 2011 (power in red and in blue)

The intelligent control valve's ability to monitor the total cooling delivered vs. flow rate, allows for a characterization of the coil response. Continuous monitoring would recognize changes in the coil characteristic over time to enable fault detection such as coil fouling. In addition, the coil performance characterization now possible is useful under operating conditions that are substantially different from the design conditions as in the case of the Hayden Library coils: The improvements reported here were achieved (in five of the six cases) with the original coils that were designed in 1947 for only a 6°F (3.3K) ΔT, i.e. rather short cooling coils. The fact that coils with such low design temperature differences can actually deliver higher levels of cooling is deemed important as it contradicts the assumption that a coil exchange is a prerequisite to improving plant ΔT performance.

As anticipated from the analysis, an effect of diminishing returns of coil output with increasing water flow is evident in Figure 4. If an operator would know the marginal benefit of pumping the last 20 GPM (1.3 L/s) through AHU-6 as well as the associated drop in temperature difference from 14 to 10°F (7.8 to 5.6K), he/she may decide to withhold the additional flow and the associated pump power, along with a marginal loss of coil capacity. However, detecting this saturation effect is not trivial as it depends on the entering air state and flow and, in particular, on the entering water temperature. In fact, in the five cooling coils retrofitted on the MA university campus, the extent of the ΔT degradation was very different. In the field study, it was decided to implement a ΔT manager strategy that limits chilled water flow such as that ΔT does not fall below 12°F (6.7K). Figure 4 reveals that this $\Delta T_{lim}$ setting indeed allows for saturation to occur, i.e. for the coil to deliver almost all of its capacity.

It should be pointed out that by monitoring the power vs. flow curve, the waste zone could be defined by either a ΔT limit or a flow limit, both values being closely related to each other. The ΔT manager implements either a ΔT limit or a flow limit for operation. Depending on the application, one setting may be preferred over the other. In the case of the MA campus case study, both strategies offered similarly good results.

In tallying the number of hours of saturation during the 2011 cooling period, it became obvious that the five (intelligent control valve equipped) air-handling units suffered from saturation and the associated ΔT degradation to very different extents, as shown in Figure 5. While AHU-4 (retrofitted with a deeper cooling coil and 14°F [7.8K] design ΔT) and AHU-1 reveal on the order of 10-15% of saturated hours, coils AHU-2, 3, and 6 are saturated between 40% and 80% of the time. Even an experienced building operator would be hard pressed to identify a priori, which of the coils in a distribution loop is most likely suffering from power saturation most and thus a device-level intelligence is preferred in identifying this condition.

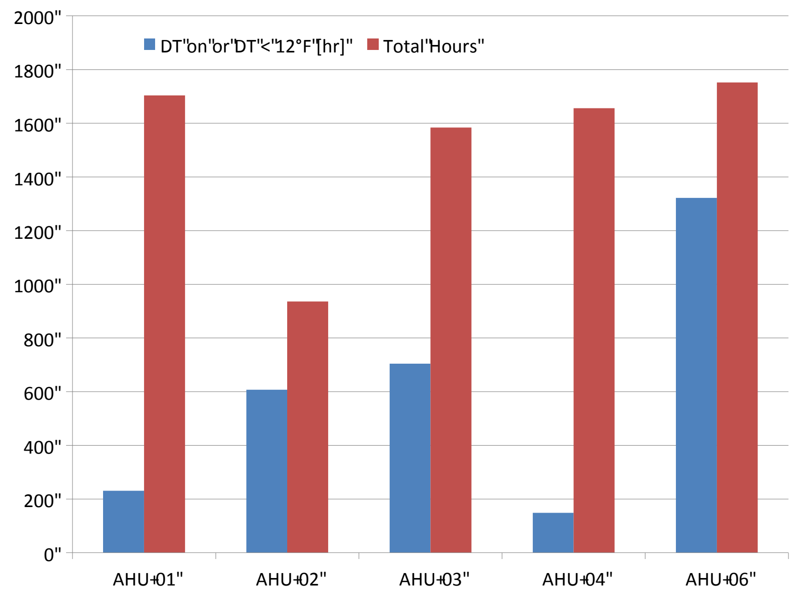


Figure 5: MA Campus Library Total and Saturated Operating Hours During 2011

An experiment similar to the one on the MA campus was repeated in Colorado. The CO campus central plant has had issues with a low ΔT syndrome from several campus buildings, which resulted in over-pumping of the central plant system and plant-wide ΔT as low as 4°F (2.2K). Its music building is one of the closest buildings to the central plant, demanding a lot of water flow with not a significant ΔT returning to the central plant and was chosen to determine whether providing pressure independent valves would free up capacity for buildings that were more hydraulically remote. Data collection in CO continues through 2012, but trends similar to Figure 6 have been confirmed. In addition, the CO campus has several buildings that need to be added to the central plant chilled water system. The pressure independence would free up more capacity as well with the hope that it could save on capital investment of increasing plant and pipe size to accommodate future growth on the campus without having to provide new or replace existing piping.

## SUMMARY

In assessing the impact of the retrofit of the six AHU (five with intelligent control valves and one with a mechanical pressure independent valve) in a library on a Massachusetts campus, it is illustrative to compare the average building-wide chilled water temperature on the district cooling system for two identical time frames of 2010 and 2011. From Aug 9 to Oct 9, 2010, i.e., before the retrofit, the building-wide average ΔT was measured to be merely 6.15°F (3.42K). After retrofitting the six cooling coils, the average ΔT of the library has essentially doubled to 12.14°F (6.74K) as confirmed by post-retrofit measurements. It is thus evident that the pressure independent valves when coupled with a ΔT management strategy have vastly improved the load-to-flow relationship of this building. This improvement allows the campus to serve additional cooling load on its campus with the same distribution and central plant system as the central cooling plant is no longer choked to deliver cooling by excessive flow requirements in the distribution loop.

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# Methods for Assessing Longitudinal Variations of Energy Production by PV Systems

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## ABSTRACT

Energy efficiency programs, such as Better Building Initiative, assume that our knowledge is adequate to understand and assess energy savings and productions, in order to guide investment decisions so that energy savings goals are achieved. However, energy savings and productions following the implementation of energy improvements, such as Photovoltaic (PV) systems, are subject to significant short- and long-term variations over time. Understanding the longitudinal variations of energy savings and productions is critical to achieve energy savings goals. The objective of this paper is to identify and characterize main properties of longitudinal energy productions following the implementation of photovoltaic (PV) systems. Graphical and statistical time series methods are used to directly extract knowledge from the actual longitudinal energy productions. The data about longitudinal energy productions of forty five PV systems were used in this study. The data were provided by Florida Solar Energy Center. The identified properties of longitudinal energy productions are outliers, level shifts, seasonalities, long-term trends, and short-term variations. It is expected that the knowledge about longitudinal variations of energy productions improve maintenance, design and investment analysis of PV systems in order to achieve energy productions goals. It is also anticipated that the proposed methods can be used for identifying and characterizing longitudinal energy productions following the implementation of other energy improvements.

*Keywords: Energy Savings, Energy Productions, Longitudinal Assessment, Photovoltaic Systems*

## INTRODUCTION

Government and private investments in building energy programs will amount to the largest coordinated monetary injection in the building stock in the U.S. history. On December 2nd, 2011, President Obama joined by former President Clinton along with representatives from more than 60 organizations to announce $4 billion in federal and private green building investments. President Obama signed a memorandum for a minimum of a $2 billion commitment from federal agencies to enhance energy efficiency in federal facilities. This was matched by a $2 billion private-sector commitment, covering up to 1.6 billion square feet of commercial and independent properties. There is an explicit federal mandate, which makes this initiative completely different from the

Energy Department's loan guarantee program: this initiative will not have any cost to taxpayers. "The private sector takes all the risk here, so the federal government is not at risk for the investments" Jeff Zients, federal chief performance officer and deputy director for management at the White House Office of Management and Budget said, adding that the companies and government will be paid back through energy productions.

Energy efficiency programs, such as this Better Building Initiative, assume that our knowledge is adequate to understand and assess energy savings, in order to guide investment decisions so that energy savings goals are achieved. However, recent studies (Brown et al. 2008; NBI 2008; Roth et al. 2005) have found on average 30% and, in some cases, up to 100% deviation between predicted and realized energy savings in building energy improvement projects. A study of high performance buildings by the National Renewable Energy Laboratory (NREL 2006) demonstrated that after implementing energy improvements, such as ground source heat pumps, under floor air distribution systems, Photovoltaic (PV) systems and high performance windows, the actual energy productions are subject to significant variations over time. These results are common and represent significant variations in energy productions following the implementation of building energy improvements. These findings underline the importance of studying energy productions over time.

The research objective of this paper is to capture and characterize the longitudinal variations of actual energy productions following the implementation of 45 PV systems. The main properties of longitudinal variations of energy productions are rigorously characterized. We directly extract knowledge from the actual longitudinal energy productions. Our approach takes into account the time-dependency of actual energy productions following the implementation of PV systems. The major properties of longitudinal energy productions are examined to enhance our understanding about the variations of energy productions over time.

## RESEARCH BACKGROUND

The literature – about the outdoor performance of PV systems over time– is dominated by studies quantifying the slope of values of performance indicators linearly over time (Ishii et al. 2011; Marion et al. 2005; So et al. 2007; Makrides and Zinsser 2010; Marion and Adelstein 2003; Sorloaica-Hickman et al. 2011). For example, Marion et al. (2005) evaluate the performance of 24 PowerLight PV systems (twenty single-crystalline silicon-based systems, two multicrystalline silicon-based systems, and two amorphous silicon-based systems) in the United States. They use the monthly performance data (Performance Ratio and PVUSA rating) from 1994 to 2004 for their analysis. They use the linear least-square fit and call the slop of line "degradation rate". According to Marion et al. (2005), the annual degradation rates calculated using Performance Ratio values for different technologies are not the same and these annual degradation rates are between 0.9 to 1.5 percent per year. This difference in degradation rates based on technology types are confirmed by other researchers as well (Ishii et al. 2011; Makrides and Zinsser 2010; Jordan et al. 2010). Jordan et al. (2010) adds that manufacturer has the list impact on the variation components of degradation rates. Marion et al. (2005) find that the values of final PV system yield over time are highly seasonal. The reason behind this seasonality is the fact that this indicator is not normalized for weather conditions. They report that the seasonality for PR values is less than final PV system yield. They also indicate that PVUSA rating shows the least amount of seasonality.

Jordan and Kurtz (2011) review the literature and identify around 2000 degradation rates reported in the literature. They report that the median of these 2000 degradation rates is 0.5%. These 2000 degradation rates are associated with various PV module types including a-Si (amorphous silicon), CdTe (cadmium telluride), CIGS (copper indium gallium selenide), mono-Si (monocrystalline silicon), and multi-Si (multicrystalline silicon). Jordan and Curtz (2011) create the histograms of degradation rates. The histograms show that the degradation rates have a probabilistic nature. Therefore, the modeling efforts should take this characteristic into account and the models should capture the probabilistic feature of the degradation rates. Moreover, the histogram of degradation rates is skewed. Therefore, the degradation rates might not be normally distributed. It can also be observed that the degradation rates can be negative. It implies that the performance of PV panels does not necessarily decrease.

Although, the literature implies that the performance of PV systems (even the most reliable ones, such as crystalline silicon (c-Si) PV systems) gradually and slightly decreases over time (Dunlop and Halton 2006; Skoczek et al. 2009), the efforts towards modeling the performance over time are limited. Jordan (2011) creates mathematical models to analyze the outdoor performance of PV systems over time. He proposes Autoregressive Integrated Moving Average (ARIMA) to model the longitudinal performance of PV systems. In another effort for modeling the outdoor performance of PV systems, Vergura (2011) uses statistical tools for diagnosing PV systems. He captures the trend of the real operation of a PV plant and uses an approach based on ANOVA and Kruskal-Wallis tests for detecting and locating abnormal operating conditions.

We study the longitudinal energy productions and formally identify and characterize the major properties of energy productions variations over time. Our approach takes into account the time-dependency of actual energy productions following the implementation of PV systems. The identification and characterization of the major properties of longitudinal energy productions is the first step towards creation of appropriate stochastic processes to model longitudinal energy productions following the implementation of PV systems.

## METHODS AND RESULTS

The main properties of longitudinal energy productions are identified and characterized. 45 PV systems (retrieved from the public PV systems dataset provided by Florida Solar Energy Center) are examined and five types of properties are identified in longitudinal energy productions. The properties of longitudinal energy productions can be characterized as outlier, structure change, seasonality, long-term trend and short-term variations. Fig. 1 exemplifies these properties for energy productions following the implementation of several PV systems in this dataset.

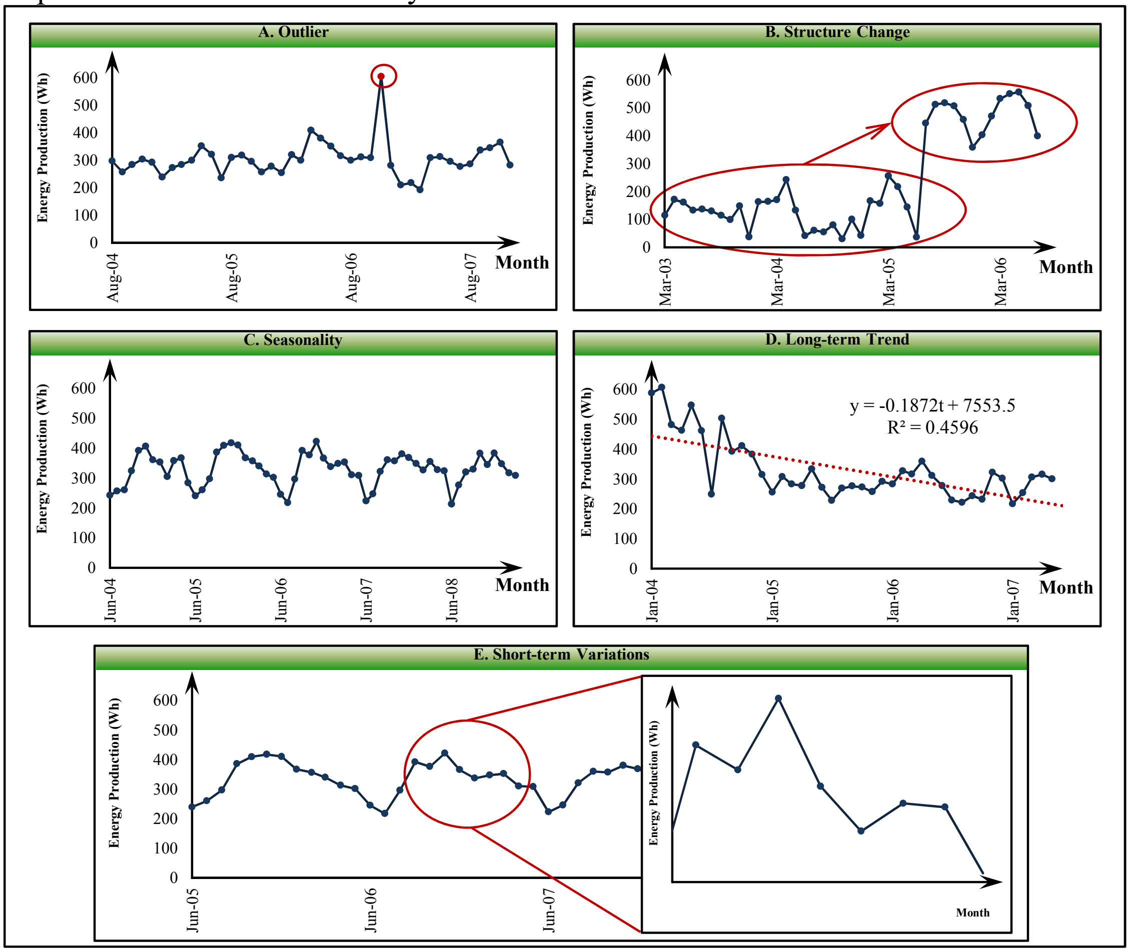


Figure 1. Main properties of longitudinal energy productions following the implementation of PV systems

## A. Outlier

An outlier can be defined as an observation that is not consistent with the remainder of observations and deviates substantially from other observations (Hodge and Austin 2004; Barnett and Lewis 1994; Grubbs 1969). The outliers of longitudinal energy productions can be due to momentary system faults, measurement errors and file preprocessing errors. These anomalous observations need to be identified and removed from the sample data, in order to characterize longitudinal energy productions properly because they can cause significant bias in the analysis of time series (Tolvi 2000; Chen and Liu 1993; Kleiner et al. 1979). Since longitudinal energy productions are dependent time series observations, absolute values of energy productions are not good measure to identify outliers (Tolvi 2000). Statistical time series tests are used for identifying and characterizing outliers. There are two types of outliers: additive and innovation outliers, which need to be identified and characterized (Tsay 1988). An additive outlier just affects a single observation whereas an innovative outlier also affects subsequent observations. The test statistic proposed by Chang, Tiao and Chen (1988) is used for identifying and characterizing outliers in time series of energy productions. Fig. 1(A) shows an example of an outlier in energy productions of the PV system installed for Daytona Beach Joint Apprenticeship and Training Committee that is identified by the method proposed by Chang, Tiao and Chen (1988).

**B. Structure change**

Structure change is the result of change in the structure of time series, such as variance change and level shift (Tolvi 2000; Tsay 1988). The structure change in longitudinal energy productions can be due to system failure or maintenance of the energy improvement. Fig. 1(B) shows an example of structure change in the energy productions of a PV system installed at Coronado Beach Elementary School in Florida. The methods created by Hawkins and Zamba (2005), Hawkins and Zamba (2005b), Hawkins et al. (2003), Ross et al. (2011), Ross and Adams (2012), and Ross (2012) are used for identifying and characterizing various structure changes in the time series of energy productions. Figure 2 represent two structure changes identified in the time series of energy productions following the implementation of a PV system installed at “A Child's Place” Montessori School at Jacksonville, FL.

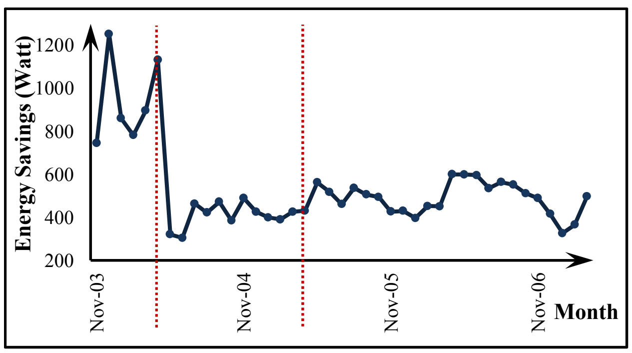


Figure 2. Structure changes in the time series of energy productions of a PV system

**C. Seasonality**

Seasonality shows periodic behavior in longitudinal energy productions. Seasonality is often highly correlated with factors other than energy improvement itself, such as weather and occupancy patterns. Seasonal movements can be large enough to cover other characteristics of longitudinal energy productions. Therefore, it is critical to determine seasonality in longitudinal energy productions. Fig. 1(C) shows an example of seasonality in a PV system at Meigs Middle School in Florida. Both graphical and statistical methods are used to identify and characterize seasonality of longitudinal energy productions. Autocorrelation Function (ACF) (Box and Jenkins 1976) of the energy productions are calculated and plotted to visually identify the lag-dependent cyclical behaviors, which are strong signals for the presence of seasonality in the time series data. Figure 3 represent the ACF plot of the time series of energy productions of the PV system at Megis Middle School. This figure shows the lag-dependent cyclical behavior of the energy productions.

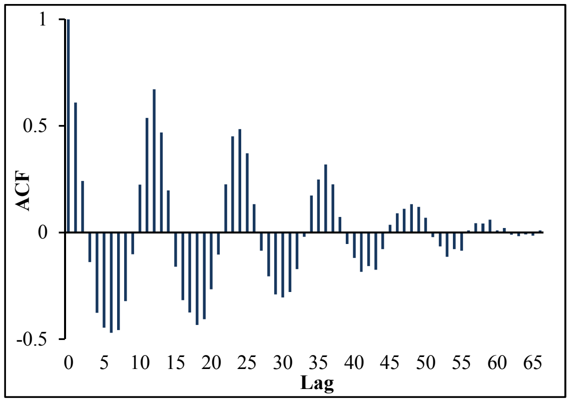


Figure 3. Auto Correlation Function of seasonal time series of energy productions of a PV system

**D. Long-term trend**

The long-term trend of energy productions are identified and characterized. Long-term trend represents the gradual change in buildings and energy improvements. The linear regression is used to characterize long-term trend in the longitudinal energy productions following the implementation of energy improvements. Fig. 1(D) shows an example of the long-term trend in energy productions following the implementation of a PV system installed for Central Florida Electrical Joint Apprenticeship and Training Committee. It depicts that energy productions of the PV system decrease substantially over the long-term horizon. Figure 4 represents the ACF plot of time series of energy productions of this PV system for lags 1 to 16 that shows the time series has a long-term trend.

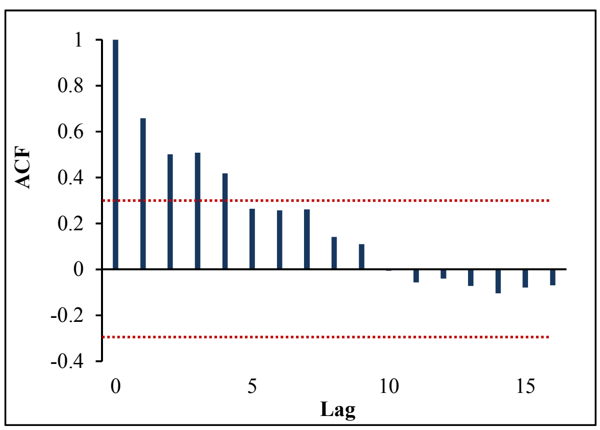


Figure 4. ACF plot of time series of energy productions of a PV system that has a long-term trend

**E. Short-term variations**

In addition to the long-term trend, short-term variations need to be characterized, in order to have a good understanding about longitudinal energy productions. It is important to know whether the short-term variations of energy productions are random or there are short-term correlations in energy productions following the implementation of energy improvements. Autocorrelation Function (ACF) and Partial Autocorrelation Function (PACF) of the energy productions are calculated and plotted to visually identify the short-term and lag-dependent features of energy productions. Fig. 1(E) shows an example of the short-term variations in energy productions following the implementation of in a PV system at Meigs Middle School in Florida. Figure 5 shows the ACF and PACF plots of the energy productions of the example (1.e) where seasonality and long-term trend are removed before plotting ACF and PACF.

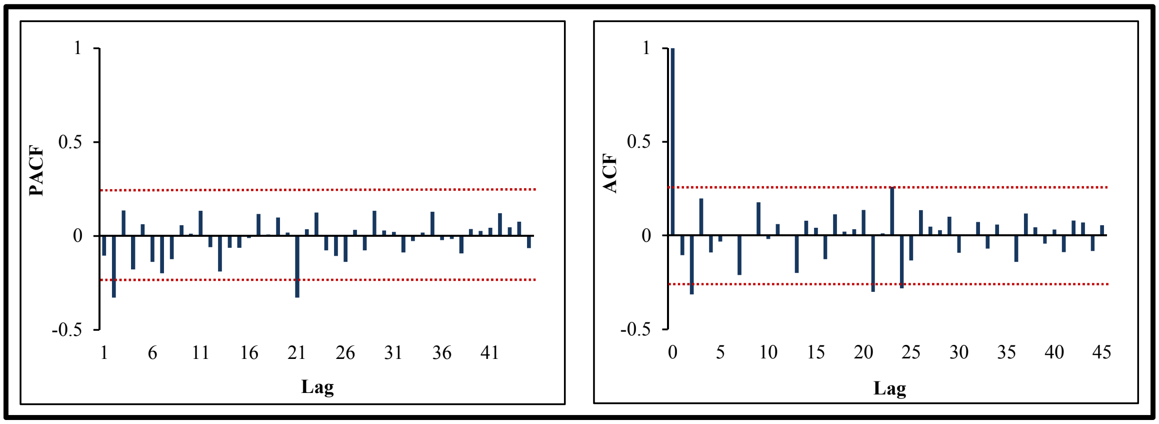


Figure 5. ACF and PACF plots of longitudinal energy savings of a PV system after both the long-term trend and seasonality are removed

## CONCLUSION AND FUTURE WORK

Proper methods are proposed to identify and characterize the major properties of longitudinal energy productions following the implementation of PV systems. The identified properties of longitudinal energy in 45 studied PV systems are outliers, level shifts, seasonalities, long-term trends, and short-term variations. These properties are identified to enhance our understanding about the variations of energy productions over time. The proposed methods can be used to determine the frequency and the average magnitude of the identified properties of the PV systems. In the future work, we will describe how frequent these properties are seen across the 45 systems and will report the magnitude of these properties. The identification and characterization of the major properties of longitudinal energy productions is the first step towards creation of appropriate models to capture the stochastic behavior of longitudinal energy productions following the implementation of PV systems. The knowledge about variations of energy productions can be used to create data-driven models, such as univariate time series models. This knowledge can also be used within existing physical models representing the performance of PV systems. For example, the expected energy production of PV systems, determined using physical models, can be modified by considering degradation of PV systems, which is basically the long term trend of energy production. The same methods can be used to identify and characterize the properties of longitudinal energy productions of other building energy improvements. It is expected that the knowledge about longitudinal variations of energy productions can also improve current practice in maintenance, design and investment analysis of PV systems in order to increase the chance of achieving energy savings goals.

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# AN APPROACH FOR CAPTURING REQUIREMENTS OF COLLABORATIVE DESIGN TEAMS TO FACILITATE EVALUATION OF ENERGY EFFICIENT RETROFIT DESIGN OPTIONS

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Four and a half million non-residential buildings in the U.S are estimated to be suitable candidates for energy retrofits (McGraw Hill, 2009). The current process of evaluating design alternatives for energy efficient retrofit projects uses drawings and 3D renderings together with documents to share energy simulation results and associated assumptions. Due to document-based information exchange, it is challenging for collaborative design teams to interpret energy implications of every design option, perform integrated analyses of design information with energy model results, and compare these energy implications with those of other design options. Immersive and interactive workspaces could improve the process by allowing teams to easily visualize assumptions and energy simulation results integrated with 3D models. Various parties are involved in collaborative design teams and each has a unique role, necessitating communication of task-specific assumptions and information requirements. Hence, there is a need to first identify what engineered information that collaborative teams should share in enabling design alternative evaluation and what visualization forms design teams would need. This paper presents an approach for capturing the information/visualization requirements of collaborative design teams as they implement and leverage immersive and interactive visualization settings. An iterative approach was taken within which virtual mockups were created using information requirements identified through brainstorming with energy modeling experts and then presented to collaborative design teams in order to acquire more information/visualization requirements. This research is part of a larger effort in the Energy Efficient Buildings (EEB) Hub at the Philadelphia Navy Yard, and uses Building 661, currently undergoing retrofit, as a case study. This paper presents the initial use case, information requirements identified, and virtual prototypes developed.

## INTRODUCTION

Buildings in the United States use approximately 41% of primary energy consumed (US DOE, 2012), showing a large potential for energy savings through the retrofitting of buildings. Collaborative design teams have the largest potential impact on building energy use since decisions made throughout the design process have a greater potential impact on energy use (IEA, 2008). Various parties are involved in the design process for retrofitting and each party has a unique role, necessitating communication of task specific assumptions and information requirements to other parties. Currently, collaborative design teams share design information (i.e., data regarding the building and proposed retrofit) primarily via 2D drawings, 3D renderings, and additional documents related to energy simulation outputs. A problem with document-based information exchange is that assumptions are not explicit and require careful investigation of documents by the other parties. Based on our observations of collaborative design review meetings, a majority of time goes to discussions of individual parties' evaluations. Since the 2D and 3D documents shared for buildings do not easily convey energy model assumptions and simulation results for retrofit design options, the design teams may overlook design options without fully comprehending the energy implications and make suboptimal design decisions. Hence, there is a need for a more integrated approach to effectively share design and energy model information among collaborative design team members during evaluation of energy efficient retrofitting options.

Immersive visualization has the potential to facilitate better communication and understanding of shared information throughout the retrofit design process. A first step in providing valuable immersive visualization is to identify (a) what information each multi-stakeholder needs to convey about the retrofitting project and design alternative options (i.e. information requirements), and (b) how to provide that information (i.e. visualization requirements). In order to determine information and visualization requirements of design teams an iterative approach was taken similar to those used in the human computer interaction (HCI) domain. When designing user interfaces, the best approach to determine requirements is an iterative prototyping process with an early focus on users, beginning with creating low-fidelity prototypes and then moving to higher-fidelity prototypes (Gould & Lewis, 1985). The approach taken follows this iterative prototyping process in order to determine what information collaborative design teams need and how that information should be provided to them to facilitate their decision making process while evaluating energy efficient retrofit options.

The long-term vision of this research is to develop repeatable processes to create immersive virtual environments in order to help collaborative design teams to make more efficient and better-educated decisions about energy efficient retrofits. This paper presents the iterative approach taken in order to determine the information and visualization requirements of design teams and provides the initial requirements found.

## RELATED PREVIOUS WORK

Related research studies can be grouped under three categories: studies on the identification of client requirements in construction projects, studies on the collaborative design process, studies on utilization of immersive visualization within the Architectural/Engineering/Construction and Facilities Management domain.

There have been studies in the literature that incorporated requirements engineering process to identification of client requirements in construction projects. Arayici and Aouad (2005) proposed a requirements engineering process for computer integrated construction that involves: contextual design, the elicitation of requirements for different use cases, and user testing of growing prototypes. Another study developed a model for identifying client requirements for construction projects (Kamara, Anumba, & Evbuomwan, 2000) that included: processing client requirements, defining requirements, analyzing/prioritizing requirements, and translating requirements (prioritizing design attributes). These requirement elicitation studies were different than what is described here in the sense that they focused on different types of parties (i.e., design teams in this case) and different types of projects (i.e., energy retrofit projects in this case).

Since various dispersed parties are involved in a typical construction project, collaboration is key in effective and efficient decision-making. Early multi-stakeholder collaboration in the form of charrettes can promote more efficient and educated decisions in the design and construction process (Robichaud & Anantatmula, 2011). Further, the integrated design process allows for maximum collaboration among multi-stakeholders. Various collaboration tools (such as AutoCAD Constructware and Bentley ProjectWise) are commercially available to support collaborative processes of multi-stakeholders.

Various research studies have evaluated the usage of such tools and immersive visualization to increase the effectiveness of design team information exchanges (e.g., Johanson, Fox, & Winograd, 2002). Interactive workspaces provide multiple displays with a heterogeneous set of tools to share information and enable dynamic information manipulation among multiple users (Johanson, Fox, &, Winograd, 2002). For instance, Rosenman et al. (2007) gave a framework for a multidisciplinary collaborative design program with 3D navigation. This consisted of a database of IFC objects, an internal model, an agent society, and a virtual world. The collaborative design program would enable designers in different locations to use various heterogeneous devices, such as videoconferencing, to share documents related to a design and use avatars to walk around and navigate within a given 3D model.

Various researchers have also evaluated immersive visualization, interactivity, and virtual reality in terms of their role in improving design and construction related decision-making processes. Virtual reality based facility prototypes (including product information, process information, and simulation information) were developed and analyzed to improve the effectiveness of design related decision making processes (e.g., Gracanin & Collura, 2004). Benefits of such virtual reality based visualization environments included: improved communication, effective exploration of shared data (e.g., Bowman et al., 2006), facilitation of better feedback from owners (Messner, Riley, & Moeck, 2006), and facilitation of evaluative and predictive conversation types as compared to existing descriptive and explanative conversations (Messner, 2006). Studies also looked at the utilization of virtual reality in construction phase. For example, virtual construction simulators were developed that enabled students to visualize the construction processes with the construction schedule (e.g., Nikolic, Jarahar, & Messner, 2009). User-studies performed with students showed that teams using the virtual construction simulator were more confident in the schedules they created. Although the immersive and virtual reality based environments have been evaluated in these various areas, there is limited research on how such immersive settings can facilitate design evaluations of collaborative design teams working on energy efficient retrofits.

## PROBLEMS IN THE CURRENT PRACTICE OF INTEGRATED DESIGN PROCESS FOR ENERGY RETROFITTING

The integrated design process is a multi-disciplinary analysis and the development of design is iterative to meet owner and energy requirements. Iterative analyses (such as energy simulations) are utilized to achieve an energy efficient retrofit design option. Due to the many different stakeholders involved in the process, there is an increased amount of information that needs to be shared with other stakeholders with diverse backgrounds.

We have analyzed an integrated design process for Building 661 at The Navy Yard. The Building 661 design team, who holds a design review meeting every two weeks, consists of architects, engineers, and owner representatives. For this retrofit project the design team leveraged the Immersive Construction (ICon) laboratory at the Navy Yard, which has immersive and interactive workspace capabilities. The research team also utilized the IBM Lab with cave automatic virtual environment (CAVE) equipment at Carnegie Mellon, and developed virtual mockups using the Building 661 energy modeling results and design alternatives. Table 1 shows the stakeholders involved in the Building 661 retrofit design project, an example set of task specific information needed by these stakeholders, and the current method of conveying that information. Each stakeholder has different requirements and conveys those requirements in various formats. This creates a need for explanation of how the information is being conveyed and where that information is located, instead of focusing on the information itself.

Table 1. Communication of task specific information in collaborative design teams

| Design team member | Information to communicate to the rest of the team | How information is currently conveyed |
|---|---|---|
| **Architect** | Architectural design options | 2D drawings, 3D renderings, 3D models |
| | Building codes | ICC codes |
| | Energy simulation results for options evaluated | Reports and outputs of energy modeling software |
| **Civil Engineer** | Structural information | 2D drawings, models |
| **MEP Engineer** | Mechanical/Electrical/ Plumbing information | 2D drawings, models |
| **Owner Representative** | Owner requirements | Specifications, contract documents, city level energy retrofit requirements |

By its nature, the integrated design process is an iterative process that requires defining design options and analyses of these design options from the energy, sustainability, and owners' perspectives using various analyses techniques that generate engineered data (e.g., to achieve energy goals, utilization of energy models and simulations). It is the responsibility of the design team to effectively comprehend the pros and cons of each design option and evaluate the options in the light of the supporting engineered data. However, the document-based nature of information exchange during the integrated design team meetings changes the focus from the information itself to the method of communication. Hence, the design teams' efficiency is sacrificed as its members try to comprehend the energy implications of options. Various interactive workspaces have been used to improve the efficiency of these design teams. However, in current practice, the integration of design information with engineered data is still left to design team members as a mental exercise. What is missing is the availability of environments where engineered data can be analyzed together with the spatial information in an integrated way. In such an environment, design team members would also be aware of the underlying assumptions about the design that govern the generated engineered data and the corresponding results, as each design option is being evaluated. This project leverages immersive settings to enable the described integration. In order to develop such environments for design teams, an essential first step is to identify what information should be presented to enable comprehension of the energy implications of the evaluated design options.

## AN ITERATIVE APPROACH TO IDENTIFY REQUIREMENTS OF INTEGRATED DESIGN TEAMS

Our initial interactions with design teams have shown that they cannot effectively describe their information and visualization requirements for immersive settings unless an example environment is provided to them. Information requirements are defined in this context as the facts, concepts, assumptions and data that are needed in order for the integrated design team to make a design related decision. Therefore, our approach includes creating virtual mockups in order to gain additional feedback about information and visualization requirements for an immersive setting. The major steps of the research approach utilized are shown listed below (Figure 1). The iterative approach should be followed until no additional requirements are obtained from the same design team.

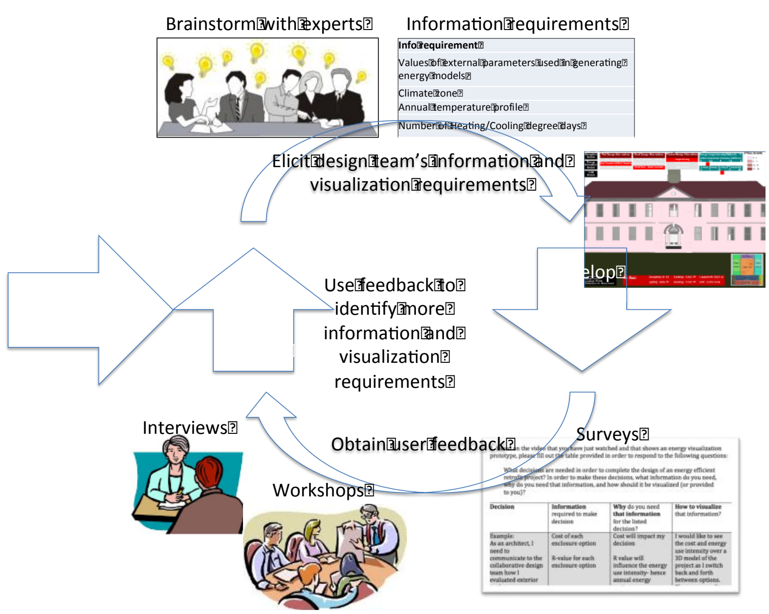


Figure 1. Approach to identify information requirements of integrated design teams

*Step 1. Define a use case*

A use case can be defined as a series of interactions between a user and the envisioned system (Wiegers, 2003). Defining a use case requires understanding the problem domain and decomposing the vision into pieces that can be developed quickly. A use case approach is essential to ensure that the system will contain the functionalities required.

To support energy retrofit design teams, we focused on the problem of integrating the engineered data with design information. To do this, the 3D model of Building 661 was obtained from the design team and the EnergyPlus model was obtained from another researcher group. Energy use intensity information for different design alternatives (roof, exterior enclosure, and windows) was generated from the EnergyPlus model.

*2. Elicit design team's information and visualization requirements*

Various approaches exist to elicit requirements of users within the software engineering domain. These include, but are not limited to: brainstorming, interviewing experts, surveying experts, and interactive workshops.

We have worked with various energy-modeling experts (from industry and academia) as well as the integrated design team to elicit their requirements for integrated assessment of engineered data with design information. Since energy modeling experts generate the engineered data, their input was indispensable for the project. We particularly used brainstorming and face-to-face interviewing approaches to elicit their requirements. Interviewees were first shown a virtual walkthrough of an immersive setting and were given an explanation of integration so that they could understand the concept of the system being developed. They were asked what information requirements design teams have when deciding on design alternatives for energy efficient retrofits, and how each information requirement should be visualized.

The initial list of information and visualization requirements identified through brainstorming and interviewing design team members and energy-modeling experts are shown in Table 2. These information requirements were used as a starting point for the development of the virtual mockup.

Table 2. Initial list of information and visualization requirements identified

| Information Requirement | Visualization Requirement |
|---|---|
| Design Options | Highlighted buttons |
| Energy Use Intensity (EUI) for each option | Bar graph |

*3. Develop a virtual mockup*

Based on the identified use case, initial set of information requirements, and visualization requirements, a virtual mockup (or prototype) was created to display the information. Creating the virtual mockup is essential because initial interactions with design team members have shown that they cannot provide reliable feedback without a way to visualize the environment. The mockup can be created through storyboards, or in a software environment, that can rapidly create mockups. For this project we focused on generation of immersive virtual mockups.

For the Building 661 project, an initial virtual mockup was created with EON Studio software, which is a commercially available software used to create and render 3D environments and can be used to display such models in immersive settings. The initial mockup (see Figure 2) contained two modules: a navigation module free of information to allow for easy travel throughout the building (this was intended for looking at the architectural design of the building), and an energy simulation module allowing the user to change design options and see the energy use intensity output of the model. The energy use intensity data was determined from the energy simulation results generated. The mockup was used to get feedback from the participants to detail their requirements.

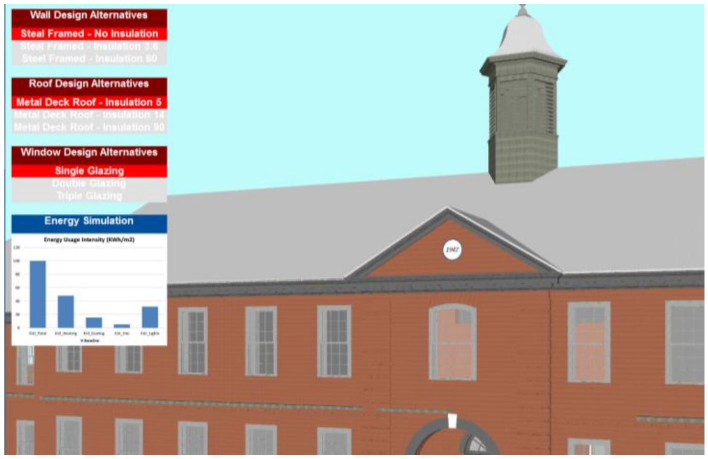

Figure 2. Initial virtual mockup

*4. Obtain user feedback*

The objective in this step is to determine if the previously identified requirements are incorporated correctly, and if there are other requirements that have not yet been identified. The most effective way for users to evaluate the virtual mockup is to have the users demo the system. However, it is also possible to do a live demonstration or even a video of the system. Once the users explore the mockup, their feedback should be queried again using the elicitation techniques described in Step 2.

The team then showed the virtual mockup (Figure 2) of the environment to users to elicit further requirements. After the first iteration of the approach, the virtual mockup primarily contained energy model simulation results and design alternatives (Table 2). Feedback from users provided further information requirements such as cost information.

*5. Iterate the process*

The feedback gathered is incorporated into the virtual mockup and list of information and visualization requirements, which are presented again for further feedback and refinement starting from Step 2.

The feedback received in the subsequent iterations with the collaborative design team and modeling experts for the Building 661 project showed that cost, energy model simulation assumptions, and thermal zones were all critical information requirements. Modifications were made to the virtual mockup to add the additional information requirements; the result is presented in Figure 3. The new version of the virtual mockup contains three modules: (1) a navigation module for easy walkthrough within the spaces; (2) an energy simulation module for viewing the design alternatives and energy model simulation results, and (3) a cost module for viewing the design alternatives' initial cost and annual energy savings. All modules contain the energy model simulation assumptions (location of building, climate information), a map of the thermal zones for that level of the building, and the current thermal zone that the user is in with associated HVAC assumptions for that zone (visualized as text boxes). The energy simulation module shows selectable design alternatives (visualized as highlighted buttons) for the exterior enclosure, roof, and windows of the building, and the resulting energy use intensity (visualized as a sliding scale bar). The cost module displays the same selectable design alternatives, a numerical value for energy use intensity, as well as the initial investment increase and annual energy savings based on the design alternatives chosen (visualized as sliding scale bars). The energy simulation module and cost module both display the color-coded R-value of the material chosen for the design.

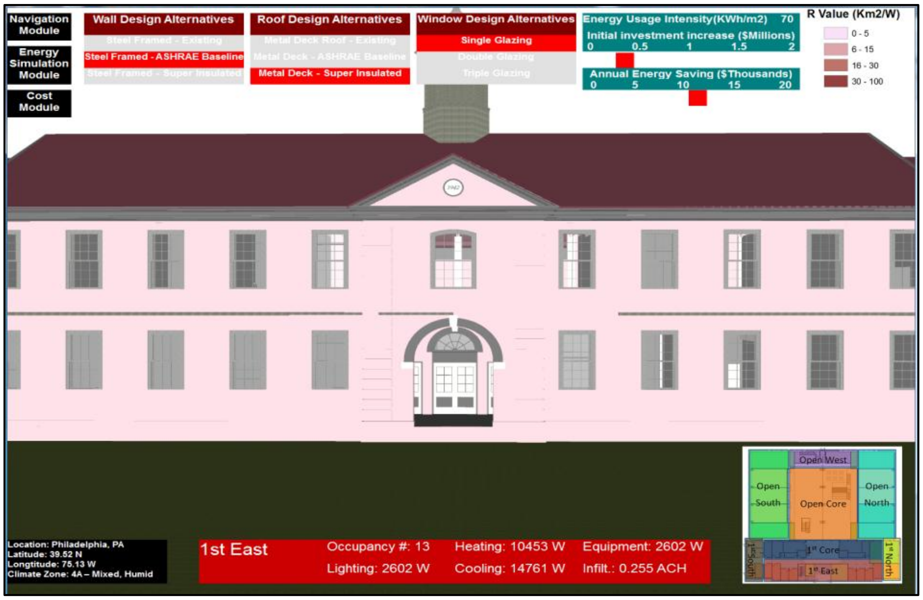

Figure 3. Virtual mockup: cost module

Table 3 lists the information requirement categories for the use case, descriptions for each category, and examples of information and visualization requirements.

Table 3. Identified information requirement categories

| Category of information | Brief description | Examples of Information Requirements | Examples of Visualization Requirements |
|---|---|---|---|
| **External Energy Model Assumptions** | Describes the types and values of assumptions that are related to external parameters used in generation of energy models | Climate zone, Wind speed and direction, Orientation of building | Text box |
| **Internal Energy Model Assumptions** | Describes the types and values of internal parameters used in generating energy models | Thermal zones, Chilled water supply temperature, Occupancy schedule | Text box, map of thermal zones |
| **Resulting Energy Use and Cost Impacts** | Describes the types and values to display for energy consumption values from energy models and cost of alternatives | Based on selected design alternative: Energy use intensity, initial investment increase, annual energy savings | Sliding scale bar |
| **Indoor Environmental Quality** | Describes the types and values to display indoor environmental quality (IEQ) | Air quality | Unknown |
| **Thermal Comfort** | Describes the types and values to display for thermal comfort | HVAC set points, minimum radiant temperature | Unknown |

The approach described in this section was an iterative one in which the research team identified information and visualization requirements associated with collaborative design of energy efficient retrofits, developed a virtual mockup including those requirements, showed the mockup to design teams, and used feedback to update requirements. This approach has been used to identify design team requirements for the chosen use case. Showing the mockup to design teams helps them to identify information and visualization requirements, while continuing to update the mockup helps ensure that new requirements will be found, and that previously identified requirements are not duplicated. This approach is advantageous for ensuring that the developed system is actually useful for design teams doing energy retrofits.

## CONCLUSION AND FUTURE WORK

An iterative approach was developed in order to identify requirements of collaborative design teams while utilizing immersive settings for evaluation of energy retrofit design options. The iterative approach is observed to be beneficial for ensuring identification of information and visualization requirements. However, because the approach is iterative in nature it takes time and requires involvement of user groups. This approach is scalable to implement in similar settings in other decision settings. Using this approach, an initial set of information and visualization requirements have been identified and presented, along with the initial virtual mockup.

Current work is focused on the process of facilitating evaluation of retrofit options by collaborative design teams, however there are many other stakeholders who are yet to be considered (facility managers, owners, etc.). The research will be extended to include these multi-stakeholders and capturing and visualizing their requirements for retrofit projects. Further use cases will be identified to consider other decisions in the energy retrofit process. Lastly, a repeatable platform will be developed so that immersive virtual environments can be created for any use case and stakeholder.

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# The Need for Change and Dependency Management in Energy Efficient Retrofit Projects

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## ABSTRACT

Changes are inevitable in construction projects and through the life of a building. In many cases, each change triggers a chain of other events which need to be managed. This makes change and dependency management one of the most critical activities in construction project and operations management. This is particularly important in retrofit projects, which are typically complex due to the constraints in the availability of information (such as original owner requirements, design and specifications and associated decisions) and limited or lack of access to the project team involved in the original design and construction of the building. This paper aims to highlight the need for managing changes and dependencies in energy efficient retrofit projects. A review of theoretical and practical issues in change and dependency is presented; including basic definitions. Insights from ongoing research in construction and other industries are used to discuss the context for change and dependency management in construction projects. The paper further examines change and dependency management issues in four case studies. Critical problems originating from poor change and dependency management, which resulted in project failures and, in some cases, catastrophic incidents, are identified from the cases. Analyses of the case study findings are informative and indicative of the importance and benefits of good change and dependency management, which need to be adopted in retrofit projects. The paper concludes by identifying critical issues in energy efficient retrofit projects which make change and dependency management vital to their success. The initial efforts in developing and implementing appropriate processes and systems for energy efficient building retrofit projects are briefly outlined. Recommendations for broader research in this area are also provided.

Keywords: Changes, Change management, Dependency management, Energy efficient, Retrofit project

## 1 INTRODUCTION

A retrofit project is the modification or conversion (not often a complete replacement) of an existing facility or structure (Sanvido and Riggs, 1993), Energy retrofits of existing buildings are important because buildings undergo system degradation, change in use and unanticipated faults over time, and such retrofits are critical in meeting energy and emission targets (Heo, Choudhary and Augenbroe, 2012). Recognizing its significance, President Barack Obama’s Plan, “Better Building Initiative”, aims among other things, to make commercial building space in the United States 20% more energy efficient by 2020 through cost-effective upgrades (White House, 2011).

Design or re-design and construction of energy efficient retrofit project requires significant amount of information and collaboration between actors from various disciplines (e.g., architects, engineers, project managers, etc.). Such projects may include integrating new technologies, incorporating automated controls making the buildings more intelligent, and adapting its performance from its occupancy and to environmental requirements (Yang and Peng, 2001). During design, several energy simulations and analysis are carried out with several amounts of calculated trials and errors in order to determine the most appropriate design, which will meet the owner's energy goals. The simulation models play a crucial role in computing potential energy savings (Heo, Choudhary and Augenbroe, 2012). The process is iterative during which decisions are made based on various factors such as budget, schedule, quality, risk and value propositions. Some of the decisions could result in changes, which coupled with other inefficiencies such as uncertainties in models, can impact negatively on achieving the defined energy goals. The process of requesting and approving changes is challenging due to several factors including the multiple stakeholders who participate in the process. These stakeholders include the project teams, who would need to contribute in the analysis of the impact of requested changes to the systems or services they are responsible for. As a result, this paper argues that it is undoubtedly clear for the need to effectively and adequately manage changes so that they are process and implemented without or with minimal impact to the energy goals. The principal aim of this paper is to highlight significant issues relating to the management of changes and how good change management practices can facilitate successful implementation of energy efficient retrofit projects. The remaining part of the paper is structured as follows: section 2 provides a brief overview of related work in change management in construction as well as other similar industries. Section 3 describes the research methodology of the study and in section 4, the cases are presented. In section 5, key issues of the cases are analyzed and discussed, which help in the definition of the need for change management in energy efficient retrofit projects in section 6. Finally, section 7 draws-out conclusions and future directions of the research.

# 2 RELATED WORK

## 2.1 Changes and Change Management

Business success in terms of product design and development, and service provision is largely dependent on avoiding or reducing process risks thus improving efficiency and effectiveness (Jallow, 2007). Risk management programs have been implemented and utilized in different industries in order to help mitigate threats and disruptions to products and services over operational lifetime. However, it is important to realize that successful management of change is the key to successful risk management (DHSG, 2011). In a construction project, changes are inevitable throughout the life cycle of a building, and change and dependency management are important aspects of construction management (Hao, Shen and Neelamkavil, 2008). A change refers to an alteration or a modification to pre-existing conditions, scope, or requirements in construction work (Sun et al., 2004). Dependency is the relationship between different components, and a change in one component must correspond with other components in order to maintain the functionality of the system (Jallow, 2011). When a change is made to a part of the project scope, design or building component, it is likely to propagate to affect other project variables, design or building elements or systems (e.g., HVAC, structural and lighting amongst others). Construction is a time consuming and complex process, and changes could happen anytime during the project. As a result, changes occur at various times in all phases, and improper management of changes will generate disruptive impacts (Motawa et al., 2007). Often in the construction industry, change orders are used by contractors to request modifications on a project and are generally for the purpose of controlling cost and schedule. However, such modifications could have negative impacts on other project variables and components in addition to cost and schedule. It is difficult for contractors to understand all of the associated dependencies and impacts when change orders are prepared and processed (Gould and Joyce, 2009). Change management as an integral process, according to Voropajev (1998), is related to all project factors (i.e., both internal and external): influencing project changes; possible change forecast; identification of already occurred changes; planning preventive impacts; coordination of changes across the entire project. Change and dependency management includes identification of change sources, investigation and management of project dependencies, evaluation of change effects, and change communication (Motawa et al., 2007). It is evident that some organizations suffer the consequences of uncontrolled changes as the change management system is continuously circumvented by personnel who view change processes as an impediment to progress (CCPS, 2008, p.70).

If changes are not properly managed, they can cause direct and indirect consequences (Senaratne and Sexton, 2008). For direct effects, the major concern is the cost of rework and time overrun, which is generated from uncertainties and poor information communication (Sun et al., 2004). Rework is re-doing unnecessary construction processes that are not completed correctly, and the cost of rework can take up 10-15% of the whole contract value, and can include changes in specifications (ibid). Indirect effects refer to the impacts that are not closely associated with a specific construction process and may have adverse effects on future plans. They can lead to the need to communicate with other project members, cash flow changes, and loss of float (Sun et al., 2004).

## 3 RESEARCH METHODOLOGY

This paper conducts change and dependency management study on four cases (i.e., two from the construction industry, one from the oil and gas and another from the chemical industry). The purpose of selecting cases outside of the construction is to adapt relevant lessons learned. This approach is appropriate as it is generally agreed that there are lessons to be gained from the experience of other industries especially in the management of projects. Fernie et al. (2003) discuss the growing interest in how the construction and development industry can improve its performance by learning from other industries. The change management case studies serve as crucial '*lessons learned*' from different industry scenarios for energy efficient retrofit projects and the construction industry in general. The paper reviews findings and recommendations of various investigation reports into project failures and industrial accidents highlighting critical contributing factors in relation to lack of good change management. It is important to note that it is out of scope of this paper to present an overarching content and technical issues found in the reports. Instead, the focus is on factors, which if removed, could have either prevented the accidents or mitigated severity (*i.e., in the case of the industrial disasters*) and those which could have contributed towards successful project delivery (*i.e., in the case of project failures*).

The first case (*i.e., the Deepwater Horizon Disaster*) study reviews the explosion of the Macondo well, an exploration well located in Mississippi Canyon Block 252 in April 2010, which was operated by British Petroleum (BP). The second case (*i.e., the 'Big Dig' Project*) is described as one of America's most ambitious infrastructure projects. The project was completed well over budget and schedule and caused catastrophe when completed (MassDOT, 2012; Greiman, 2010). The third case (*i.e., the Flixborough Explosion*) was an explosion of a chemical plant in Flixborough, a town in England in 1974 (DOE, 1975). The plant was used for the Production of nylon. This case was selected due to the magnitude of the destruction that followed and the inefficiencies related to change management that contributed to the explosion. The final case was the *Scottish Parliament Building Project* in Scotland, which was completed well beyond budget and time. These cases were selected because of the magnitude of the disasters and project failures, and the evidences of inefficiencies related to change management amongst the contributing factors. This paper reviewed investigation reports on the cases (National Commission, 2010; BP, 2010; US DOT, 2000; DOE, 1975; Fraser, 2004) as well as other related publications on the cases. In all cases, the incidents of disasters and project failures, and the reports, highlight key transferable aspects of change management, including the analysis of changes, identification of impact, which are crucial to enable rigorous mitigation planning. Fundamental issues relating to change management are identified and discussed. Analysis of the critical factors from the cases helps formulate key aspects of good change management and the need for its application in energy efficient projects.

# 4 CASE STUDIES AND FINDINGS

## 4.1 The Deepwater Horizon Explosion

The explosion of the Macondo well was described as the biggest 'blow-out' in history. This occurred following uncontrolled flow of oil and gas amongst other materials out of the riser, which had a drilling pipe inside it. The riser connected the Blowout Preventer (BOP), which was attached beneath the ocean to the rig. The BOP was supposed to seal the well in case of uncontrolled surge of oil and gas, which failed. As a result, hydrocarbons reached the surfaced of the ocean and caused the Deepwater Horizon rig to ignite and explode. Consequently, the explosion killed eleven workers and injured several others. In addition, million barrels of oil spilled into the Gulf of Mexico causing one of the most extensive oil spills in US history. This was incomprehensible because prior to the incident, a cementing engineer who was working on the well, sent an e-mail from the rig Deepwater Horizon, to his colleague and said "We have completed the job and it went well" (National Commission, 2010, P.1). The explosion and spill caused extensive damaged to marine and wildlife; fishing and tourism industries within the gulf region. Several factors (both managerial and technical) were attributed to the blowout including lack of adequate management of changes. Initial well design decisions undergo a serious peer review process and changes subsequently subject to a management of change (MOC) process. However, the National Commission (2010, p.122) investigations found that "changes to drilling procedures in the weeks and days before implementation are typically not subject to any such peer-review or MOC process." Risks associated with late changes to well design and procedures were not adequately identified or addressed by BP's management process. The National Commission (ibid, p.104) also indicates that numerous changes to the temporary abandonment procedures in the two weeks leading up to the day of the blowout by BP's Macondo team were made, and there was no evidence the changes went through any sort of formal risk assessment or management of change process. Emphasizing this evidence, comparable observation by DHSG (2011, P.10) indicate that the Deepwater Horizon disaster has similarities to the BP Texas City refinery disaster, which include '*improper management of change*'. Apart from the two changes demanded by BP, they were not informed of other modifications prior to them being made (BP, 2010, p.178). Failure modes or effects related to the modifications or post-modification verification testing requirements were not identified by the management of change process of Transocean (ibid). Efforts were made to actuate the BOP. However, it was not realized early on that the stack's plumbing differed from the diagrams on which both BP and Transocean were relying, and to inform the engineers attempting to trigger one of the BOP's rams through a hydraulic panel that they had been misdirecting their efforts. "W*ithout properly recording the change*, Transocean had reconfigured the BOP; the panel that was supposed to control that ram actually operated a different, "test" ram, which could not stop the flow of oil and gas" (National Commission, 2010, pp.137-138). BP (2010, p.36) in a list of key findings specifies that BP Macondo well team could have raised awareness of the challenges of achieving zonal isolation and led to additional mitigation steps by improved technical assurance, risk management and management of change.

### 4.2 The 'Big Dig' Project

According to MassDOT (i.e., the Massachusetts Department of Transportation) (2012), Boston's Central Artery/Tunnel Project (CA/T), commonly referred to as '*the Big Dig*', is recognized as the largest, most complex, and technologically challenging highway construction project in the history of the United States. The Project was aimed to significantly reduce traffic congestion and improve mobility through the city of Boston. Work began around the early 80s and finished, more or less in 2007. The scale and scope of the project compounded the challenges. The project, which included the reconstruction of I-93 incorporated a new eight-lane highway beneath the existing elevated Central Artery through downtown Boston, and the extension of I-90. The I-90 extension involved placement of a four-lane immersed tube tunnel beneath Boston Harbor. It also comprised the building of several bridges and tunnels, including the Ted Williams Tunnel, which extends Interstate 90 to Logan International Airport (MassDOT, 2012, Greiman, 2010, US DOT, 2000). The project was affected by delays, engineering difficulties, and cost overruns costing over $14 billion from the initial budget of about $2.56 billion. The project had included 118 separate construction contracts, with 26 geotechnical drilling contracts and about 5,000 workers during the peak of construction (MassDOT, 2012). This contributed to the enormous difficulties of collaboration and integration between the project teams. Several reasons were documented to have been the cause of this, including frequent design changes, and changes in schedules and milestones, which the project faced (Greiman, 2010). A joint venture of two companies managed the project working as consultants. The companies had their own people doing design, which was also subcontracted by them to other consultants. However, according to Poole and Samuel (2011, p.3), the project became notorious for bids being put out with incomplete designs and sketchy data on existing conditions. As a result, contractors found themselves with hundreds of change orders, regardless of many years of pre-construction design. The scope of the project continued to grow as it is developed, thus adding unanticipated elements and unforeseen complexity (ibid, p.4). The project had to deal with many unanticipated conditions and a large volume of claims and changes. There were frequent design changes coupled with design flaws, and changes in schedules and milestones. There was a management of change to control cost but this was purely based on cost. According to US DOT (2000, p.15), "the greater the dollar size of the change, or impacts to the CA/T Project, the farther up the management levels the change has to be approved." Amongst the root causes of the delay and cost over-run was lack of experience and knowledge about dealing with the complexity and uncertainty

### 4.3 The Flixborough Explosion

June 1974, Flixborough chemical plant owned by Nypro (UK) Ltd exploded. This resulted in the death of 28 workers on the site and 36 injured in the factory. The explosion had a massive effect within the vicinity of the plant and caused widespread damage to about 2, 000 properties and 167 businesses resulting in over $10 million worth of damages (CCPS, 2005). The DOE (*i.e., Department of Employment, UK*) (1975) reported that the cause of the explosion was ignition and rapid acceleration of deflagration, possibly to the point of detonation of a massive vapor cloud by the escape of cyclohexane. The escape emanated from a section of the plant devoted to the production of cyclohexanone cyclohexanol. The plant operated 6 reactors lined and interconnected by 28-inch diameter lines with corrugated expansion bellows installed together to recirculate the cyclohexane continuously. Reactor 5 developed leak and was removed for repair. In order for the plant to continue operations without having to wait for the repair to complete, a tentative measure was adopted by installing a temporary piping to bridge the gap between Reactor No. 4 and 6. This bypass assembly failed to perform as expected due to its unsatisfactory design features. The immediate cause of the main explosion was the rupture of the 20 inch bypass assembly between reactor No. 4 and reactor No. 6. Whittingham (2004) identified that human error was also another factor that contributed to the disaster. These include: inadequate design and support of the bypass pipe in the incorporated dogleg in the piping jumper because of the elevation changes; failure by designers to recognize or communicate the consequences of not operating the reactor stirrers at start-up and changes to the design should have been overseen and approved by properly qualified personnel. Investigations further revealed that Nypro did not have adequate system for evaluating and controlling changes to ensure safety was not impacted. In fact, it was observed that currently matured perspective on Management of change (MOC) did not generally exist with industry in 1974 (CCPS, 2005). DOE (1975) and CCPS (*i.e., Center for Chemical Process Safety*) (2008) concluded that an effective

MOC system should have discovered the design flaw prior to implementation of the change, thus averting the disaster.

### 4.4 The Scottish Parliament Building Project

The Holyrood Building Project was the construction of the Scottish Parliament Building in Scotland. It was originally budgeted for £50 million in the early days of the project but the final cost at completion was estimated at £414 million. The Project commenced in 1999 and was completed and handed-over in 2004, over 3 years late. The building was completed over budget, well beyond the schedule and caused a public outcry. Consequently, a public inquiry was setup to investigate the cost over-run and the delays in the construction of the building. Several factors were reported to have been the cause with some attributed to *major design changes*, in particular, redesign of the debating chamber and increased space requirements. These included changes in the brief during the period of appointing the architect. Amongst the changes was demand to increase space and occupancy resulting in the brief specifying a building with three entrances, as oppose to the original proposal of two entrances (White and Sidhu, 2005, p.9). Value Engineering (VE) was utilized in the project to determine whether the major elements of the design provide value in relation to their costs; whether a different approach might offer a better value, and whether the value from the design could be increased within existing costs (Auditor General for Scotland, 2000). However, despite the application of VE, cost was rising. Design proposals had been unable to match the over optimistic gross/net proportions in the brief, and the need to incorporate an additional formal entrance to the building had been recognized and imposed additional space demands and therefore costs (White and Sidhu, 2005, p.11). Fraser (2004) reported that the change requests were costed using the CRFs, but it was understood that costing took no account of any consequential effect on programme, or trade package interfaces. Furthermore, it was concluded that "*there should have been change control procedures based on a detailed cost plan agreed between all parties at an early stage (Auditor General for Scotland, 2000, p.7).*" However, Fraser (2004) noted that arrangements were made for a formal change control procedure to be instituted; no steps were taken actually to amend the brief during the design development until when Stage D was finally reached. "It suggests to me that over that crucial period in the development of the Project, sight was lost of the terms of the brief. If that is correct, much of the extensive design development over that period was not taking place against the background of the clearly formulated set of client or user requirements, which the brief should have contained" (ibid, p.74). Amongst other recommendations given was the assessment of any proposed design (ibid).

## 5 ANALYSIS AND DISCUSSION OF THE CASES

It is a clear testimony that the incidents and project failures of the cases have had a magnitude of effect not only on the companies and projects involved but also on the communities in which they operated. Whilst several efforts were made to handle the consequences, one of the most important things was to identify the critical factors of the underlying causes in the first place and to make recommendations to enable the prevention of such accidents and projects failures in the future. Evidence demonstrated several contributing factors, and that lack of or inadequate management of changes related significantly in all of the cases. A common trend in all the four cases was the failure to recognize a change as a change, and there was no clear and explicit definition of what is regarded as a change. In addition, no specified management of change procedure was followed at all times. It was a common problem for assessing or adequately assessing the potential impact of changes (*i.e., safety impact in the case of Deepwater Horizon and Flixborough incidents and cost and schedule impact in the case of 'the Big Dig' and Scottish Parliament Building Project*).

It was also concluded that any Safety and Environmental Management Program (SEMP) should include methods on how to perform management of change task. According to DHSG (2011, PP.118-119) the application of risk-based design practices is required to reduce risks to ALARP (*i.e., As low as Reasonably Practicable*). It was highlighted that risk assessment and management according to good design principles should be applied when choosing between options or concepts. This would require a great deal of change management, which is crucial to successful risk management. BP being the lease operator of the Well was not aware of some of the changes made to the BOP. This did not align with good change management principles. In a well-defined and instituted change management process, all parties, in particular those who may be concerned should be informed of changes prior to their implementation. It is very difficult or virtually impossible to identify all impact of change even where a change management process is utilized as in the case of the Deepwater Horizon disaster. Therefore, despite having a standardized change management process in place, it is critical that the process is rigorously utilized and adhered to. In such way, no change will be implemented without going through the approval process and communicated widely to all those concerned. In the Flixborough incident, changes to the design of the reactors were made and implemented without going through a change management process. As a result, the changes did not meet the design specification of the equipment. This was done hurriedly in order for operations to continue, neglecting the potential consequences of the change. In a similar fashion, within the 'Big Dig' project, "problems during construction are resolved at the lowest level possible so that the contractor is not delayed. Contractor delays present time and money costs to the CA/T Project" (US DOT, 2000, p.15). If some of those problems were change related, then good change management principles might have been affected.

Multiple contractors were involved in the Deepwater Horizon who all needed to coordinate processes and efforts in order to facilitate oil exploration. According to BP (2010), no single action or inaction was identified as the cause of the accident. Rather, a complex and interlinked series of factors including: mechanical failure, human judgments, *engineering design* and team interfaces allowed the initiation and escalation of the accident. The National Commission (2010) indicated that most of the mistakes and oversights which resulted to the event can be traced back to overarching failure of management. Better management by improving the ability of individuals involved to identify the risks they faced, and to properly evaluate, communicate, and address them would almost certainly have prevented the blowout. Managing changes on-real time basis is critical to avoiding the occurrence of serious incidents. The ability of management, in particular those involved in projects with highly integrated teams and systems should have the ability to see the bigger picture to reduce the likelihood of risk and serious errors. This helps decision makers to recognize the importance of developing situations and can rapidly adapt to and successfully manage change on real-time (DHSG, 2011). It is clear from the Deepwater Horizon disaster and the Flixborough cases that managing change is not only relevant for project budget and schedule control, but crucial for other issues such as safety and performance goals. Therefore, any modifications to project scope should be rigorously processed through the standardized change management process for approval before implementation. This is important because inadequate reviews of proposed changes can result in certain changes violating energy efficient goals and design basis. This paper believes that it is the failure to: (i) have in place a standardized change and dependency management process, and (ii) incorporate such processes into energy efficient retrofit workflow, which will contribute in failure to meet energy efficiency goals.

# 6 MANAGING CHANGES IN ENERGY EFFICIENT RETROFIT PROJECTS

## 6.1 The Need for Change Management

Either small or large scale, energy efficient retrofit design and development require multi-scale and multi-discipline interactions during which several decisions are made. Often, these decisions result in some changes to project variables. This is realistic because repeatedly requirements and/or design parameters are altered to generate most optimal energy models. However, it remains doubtful if those alterations are right to meet the defined goals, and what impact they would have across other components. In fact, dependency and impact analysis of those alterations is generally not analyzed systematically. Similarly, the rationale for the alterations is often not documented for future reference, and decisions of the choices are based either on assumptions or experience. In energy efficient retrofitting, achieving energy efficiency goals is amongst the most important variables. Parties involved in an energy efficient retrofit project not only need to collaborate with other trades, but also have to coordinate with the original design drawings and specifications of the building (if available). As a result, such projects would need to review any change request against owner’s energy efficiency goals and values, not mainly against budget and schedule.

## 6.2 Potential Benefits

Considering that different people (*i.e., engineers, projects managers and other stakeholders*) are repeatedly involve in modeling and analyzing models for energy efficiency using several tools and making multiple decisions, it is vital to develop and implement a change and dependency management process and system for energy efficient retrofits. A successful outcome of managing changes depends on the multidisciplinary project team collaboratively employing and utilizing a well-defined and documented change management process and its associated information technology tool. In the context of integrated project delivery (IPD), an IT tool such as an automated process management system can be leveraged to facilitate the coordination and control of the iterative process of change request and approval. Such tools will enable a collaborative endeavor for effective change management and in overcoming its challenges. This will enable project teams to collaboratively request and implement changes in an orderly and accurate manner. Such systematic approach provides a coherent and standardized process along with supporting information exchange items to ensure effectiveness and quality in the approval and implementation of requested changes. It will contribute to avoid or minimize the likelihood of implementing changes that will impact negatively on energy efficiency requirements and goals, and maximize value for the owner. Implementing an automated system of the change management process is advantageous than a paper-based. It is better suited for tracking, automatic routing, impact analysis and even automatic reminders and escalation of the most urgent change requests. Therefore, a change and dependency management process should be embedded within the overarching energy efficient retrofitting workflows.

# 7 CONCLUSIONS

This paper reviewed the management of change and dependency from different industrial cases and presented critical factors that resulted to disasters and project failures of the cases. It highlighted factors of good change management that could have avoided or mitigated the severity of the impact. The proper application of good change management principles examined can help in the successful design and delivery of energy efficient retrofit projects within development schedule and budget; operate and manage lifecycle cost and risk, resulting in safer and more reliable and sustainable energy efficient buildings. In order to successfully achieve the objective of a state-of-the-art modeling platform for energy efficient retrofit buildings, a well-documented, coordinated and clearly communicated change and dependency management process should be used and followed by project teams, and an associated automated system be developed and implemented; this is indispensable. The big challenge for the construction industry is a shift in culture on change management. For example, learning from the CCPS, seasoned construction engineers may feel as though a change management process and system 'second guesses' their judgment/assumptions even though they are the experts, or project managers may dislike having to 'get permission' from others to make a change because progress will be delayed. Further research to investigate and develop a change and dependency management process for use in energy efficient projects has been initiated as an extension of this work. The initial process consists of standard discipline activities that project teams can follow to ensure a systematic and consistence set of practices with every change request during energy efficient retrofit projects. The activities include: identification of change and making a request, change assessment (includes dependency, impact and risks), approve, document & communicate, implement and capture lessons during post-implementation review). It is anticipated that the process when fully developed and adopted, will ensure that changes are implemented only after appropriate considerations and adequate analysis of their impacts on energy efficiency goals.

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# FINISH MATERIALS OF HOSPITAL OPERATING ROOMS OF THE USA AND EGYPT: SELECTION AND ACTUAL PERFORMANCE-IN-USE

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## ABSTRACT

The materials selected in finishing the surfaces of operating rooms can have an effect on performance. They must be suitable and supportive to the functions of these specialized spaces. Also, they must withstand the various demands resulting from the intensive use. This is especially important with the strict aseptic techniques that are typically observed in these spaces. This can also result in increased hospital operation and maintenance costs.

This paper reports on the results of two surveys on the finish materials used in the floor, walls and ceiling surfaces of operating rooms. The study covered more than 546 operating rooms in more than 86 hospitals. The first survey was conducted for hospitals built –or renovated in the USA between 1980 and 2003. The second survey was conducted in Egypt for hospitals built, renovated, or under design between 2008 and 2012. The time difference between the two surveys was of little concern, since the performance of finish materials does not become apparent except after long term use that extends for years. The surveys identified the materials that were most commonly used in finishing the operating rooms in both countries. Also, views of the facility managers of the USA hospitals in regards to the actual performance of these materials were collected. These were compared with previous studies in Egypt and the USA.

The paper draws useful conclusions to architects, administrators and facility managers on the most popular finish materials used in these specialized spaces. Also, views of the facility managers on the performance-in-use of these materials were identified. This included performance of the most popular materials in regards to their sterile properties, durability, maintenance, aesthetics, comfort, safety and cost.

Keywords: Egypt, Finishes, Hospital operating rooms, Performance, USA.

## INTRODUCTION

Hospital operating rooms house the most profitable procedures (Cima et al., 2011). The profitability of these procedures can quickly be offset by the costs of construction, operation inefficiencies, and safety risks. A properly designed operating room (OR) should contribute to efficient operations, prevent unnecessary costs, and mitigate injury to patients and staff. The benefits of molding the design of a hospital to infection control principles will have an effect that typically lasts for at least 30 years. Wrong decisions are difficult and costly to rectify (Wilson, 2006).

Hospital design and construction materials have a considerable effect on both the environment and patients' health (Vittori, 2002). In an extensive literature review study, Ulrich et al (2008) explained that the literature supports the effectiveness of choosing easy-to-clean wall finishes as means for control of cross infection. However, it was noted that the efforts that evaluate and compare various wall finishes based on performance criteria like infection control are scarce. Wilson (2006) argued that although the contribution of the environment to hospital acquired infection may be unresolved, few would disagree that hospital design is of paramount importance as means of preventative medicine. Boyce (2007) indicated that a recent report cited over 120 studies linking the hospital physical environment to infection. A similar observation was made by Reiling (2007) who argued that physical, contextual, and organizational aspects set the stage for the majority of errors in healthcare settings. In a study by Lankford et al (2006), the importance of wall finishes as means of cross infection was demonstrated. The study observed that commonly used wall finish materials were capable of transferring the pathogen through hand contact. Furthermore, Sharpe & Schmidt (2011) explained that use of cleanable smooth surfaces and open configurations that facilitate cleaning of hospital surfaces mitigates the rates and acquisition of Hospital Acquired Infections. Also, Ayliffe (1991) and Demir (2009) explained that the environmental surfaces are one of the factors that contribute to the risk of contamination in operating rooms.

Several studies addressed the criteria for selection of finish materials. In a study by Lavy (2012), hospital facility managers in Texas identified infection control and gas emission as the most important criteria for selection of surgical suite wall materials. These were followed by indoor-air-quality, ease of maintenance and sound resistance. Durability cost of maintenance, flame resistance, aesthetics, initial cost, and ease of installation, were ranked at lower rates. Additionally, Blakey & Rohde (2002) observed that healthcare facility designers consider the following characteristics in the selection of materials for a healthcare facility, in a declining order: aesthetics, durability, ease of maintenance, client preference, initial cost, cost of maintenance, infection control, ease of installation, and life-cycle cost. Schultz (1981) identified the criteria for selection of operating room walls finishes. He indicated that the walls should be hard, non-porous, and free of joints and crevices which harbor dirt. Also they should be easy to wash and withstand repeated contact with strong cleaning agents. Wilson (2006) indicated that infection control required the floor to be smooth, impervious and coved to the wall with any seams sealed. Abreua & Potter (2001) recommended that wall finishes of a surgery unit should be hard, nonporous, free from joints and crevices, easy to wash and able to withstand repeated contact with strong cleaning agents. Hart (1998) explained that all finishes should tolerate treatment for bacterial and fungal agents, because a hospital is vulnerable to the spread of infections caused by the presence of sick patients. On another note, Shafie & Sherif (2010) explained that finishing materials play an important role in construction costs whether in initial or running & maintenance costs. They argued that it is always prudent to evaluate and compare cost with the material's efficiency, cleaning method and durability.

Little literature addressed the selection of the operating room (OR) finish materials, although this is one of the factors that affect performance. Also, very little research examined the selection of these materials on a global scale, where the contrasting conditions of two different countries can highlight the importance of the factors of selection. Some critical factors might prove relevant in different countries irrespective of their conditions, while other factors might be affected by the drastically different operational environment of different countries.

## OBJECTIVE

The objective of this paper is to address the selection of finish materials in the operating rooms of hospital buildings. It focuses on the floor, wall and ceiling finishes. This paper addressed the following questions:

1. What finish materials are most commonly used in the operating rooms?
2. How different are the material selections in two contrastingly different countries: Egypt and USA?
3. What is the performance-in-use of the most commonly used materials?

## METHOD

In order to address the above questions, data about the finishes used in existing, or under-construction, hospitals were collected in two dramatically different countries: the USA and Egypt. This helped highlight the importance of the factors affecting selection of the operating room finishes. Some critical factors, such as infection control, proved relevant in both countries irrespective of their drastically different local conditions.

Data was collected from 28 teaching hospitals in the USA and 58 public hospitals in Egypt; a total of 86 hospitals. The USA hospitals included 339 operating rooms (ORs), while the Egyptian hospitals included 207 operating rooms. Thus, this study reports on the finishes of 546 operating rooms in total.

The USA study was based on a mail-out survey questionnaire to hospital facility mangers. It collected information about the finish materials actually used in the walls, floors, ceiling and doors of ORs. It sought the views of facility mangers in regards to the actual performance-in-use of the finish materials used in the ORs. Evaluation was done on a scale of 1 to 5; where 1 was for very bad performance, and 5 represented an excellent performance. The questionnaire was sent to the facility mangers of 445 teaching hospitals on August 2003. The responses were for hospitals that were constructed –or renovated- between 1980 and 2003.

Performance evaluation included the following aspects:

1. Sterile properties: porosity and water tightness, surface texture and grooves, amount and size of seams and joints and amount of pitting or cracking.
2. Durability: resistance to impacts, resistance to stains, resistance to cleaning agents, resistance to abrasion, resistance to frequent washing, and resistance to peeling from under layer.
3. Maintenance: ease of cleaning, frequency of repair / patching, ease of repair and patching and access to electrical / mechanical services
4. Aesthetics: color (pleasing and restful to eye), clean looking, and attractive appearance.
5. Comfort: underfoot comfort, underfoot warmth, ease of locating dropped items, and glare and light reflection.
6. Safety: slip resistance (wet conditions), fire safety properties, and effect on indoor quality.
7. Cost: initial cost, maintenance cost (material, labor, etc.), time wasted in maintenance, and the useful life span of material.

A different data collection procedure was adopted in Egypt due to administrative and logistical limitations that limit the yield response of mail-out questionnaires. Data was directly collected from the Technical Support & Projects Unit of the Egyptian Ministry of Health and Population, which is responsible for the architectural/engineering aspects of all public hospitals in Egypt. The data covered the hospitals, which were either renovated or newly constructed between 2008 and 2012, the hospitals which are currently under rehabilitation and expected to be completed during 2013, and the hospitals which are currently in design, either for rehabilitation or new construction. The time difference between the USA and Egyptian surveys was of little concern since the effect of material selection and performance does not become apparent except after a long term use that extends for years.

## RESULTS AND DISCUSSION

**Finish materials used in the operating rooms of Egypt and the USA**
The following is a summary of the results of survey on the materials used in the ORs of the sampled Egyptian and USA hospitals. These results represent the material preferences of the decision makers during the stages of design and construction of these hospitals.

**Floor finishes**
The materials selected for finishing the floors of the 546 surveyed ORs was dominated by sheet vinyl (figure 1). This material was used in 100% and 84.7% of the operating rooms in Egypt and the USA respectively. Other materials were used in a small number of ORs in the USA sample. These included epoxy terrazzo (8.6%) and ceramic tiles (6.2%). It is interesting that the environmentally friendly linoleum was used in only 0.6% of the USA cases.

The above results concur with those of earlier studies. Schultz (1981) indicated that a very hard vinyl floor covering on a concrete base was acceptable, providing that the seams are heat-sealed and the vinyl adheres to the concrete by a non-water-soluble material. Also, an earlier study by Shafie et al (1997) reported that vinyl floors were used successfully in the majority of surveyed ORs (30%) in Egypt.

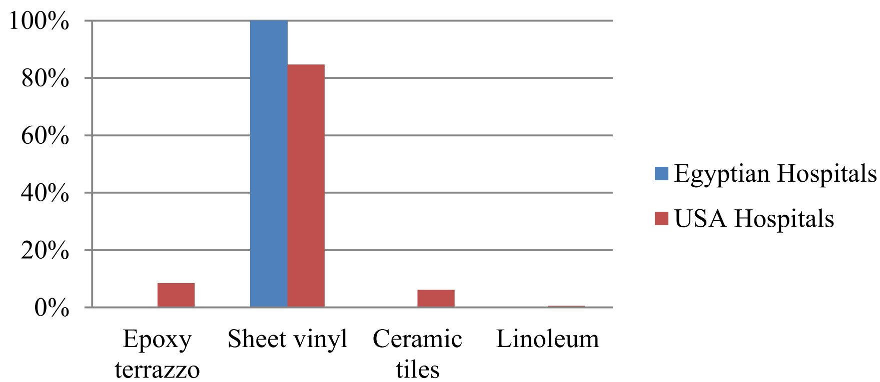


Figure 1: Frequency of floor finish materials use

**Wall finishes**

The materials selected for finishing the walls of the surveyed ORs was dominated by paints (figure 2). Paint was used in 67.6% and 60.6% of the operating rooms in Egypt and the USA respectively. Epoxy paint was the most commonly used type of paint. It was adopted in 67.6% and 41% of the Egyptian and the USA ORs respectively. PVC/ Corian / vinyl wall coverings were the second distant finish materials (25.83% and 32.1% in Egypt and USA respectively). It is interesting to note that stainless steel panels were used in only 0.2% and 0.8% of the Egyptian and USA ORS despite the high levels of performance. This is probably due to their exorbitant cost. Also, porcelain tiles were used in only 7.5% of the USA ORs.

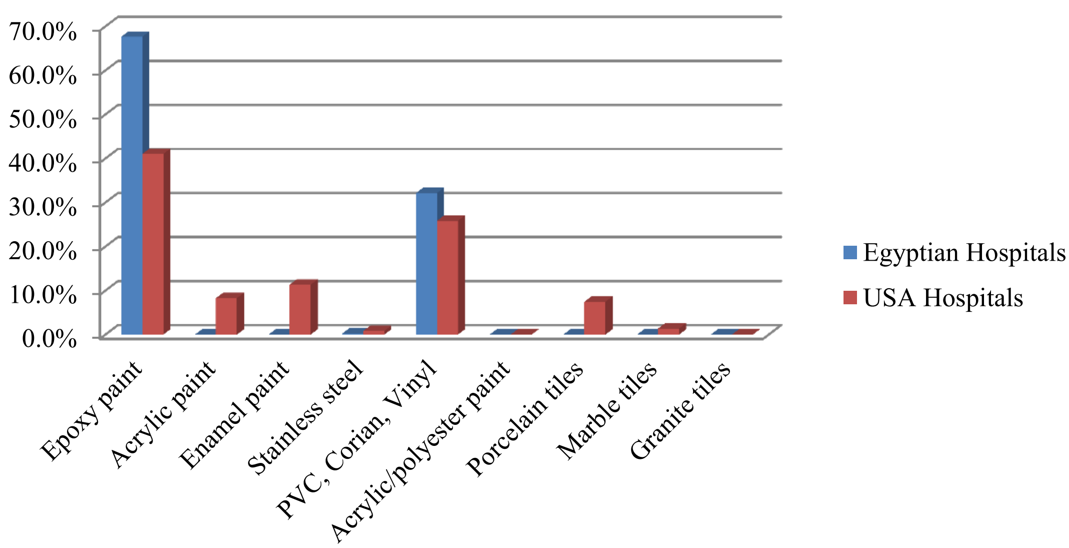


Figure 2: Frequency of wall finish materials use

These results support the recommendations of earlier studies such as the work of Abreua & Potter (2001) which indicated that ceramic tiles were not recommended in the OR walls because the many joints that were difficult to keep clean. Also, Schultz (1981) which recommended use of laminated walls with three coats of polyethylene that withstand wear and with an additional coat of epoxy paint; and the survey by Shafie et al (1997) which reported that epoxy paints and stainless were more successful in the operating rooms walls in Egypt as they facilitated ease of cleaning / disinfecting to the highest standards. Emulsion paints ranked lowest in regards to durability, and were equal to other materials in regards to ease of cleaning and disinfecting.

Furthermore, the results of this study supports Lavy's observations (Lavy, 2012) that the preferences of facility "managers" could differ from those of the facility "designers" who selected the materials of construction of the surveyed hospitals. The outcomes of Lavy's study indicated that hospital facility managers in Texas preferred vinyl for wall finishing, and the second most preferred material was paint (water based or latex).

**Ceiling finishes**

By contrast to the previous surface finishes, the materials selected for finishing the ceiling of the surveyed ORs varied dramatically between the Egyptian and the USA ORs (figure 3). In Egypt, the ceilings were made of tiles having different types (metal, anti-bacteria and/or sound absorbing). While in the USA, it was dominated by paints at a rate of 69.8%. Acrylic and Epoxy paints were most commonly used in the USA ORs (33% and 23% respectively). Ceiling tiles were used in only 12% of the USA ORs.

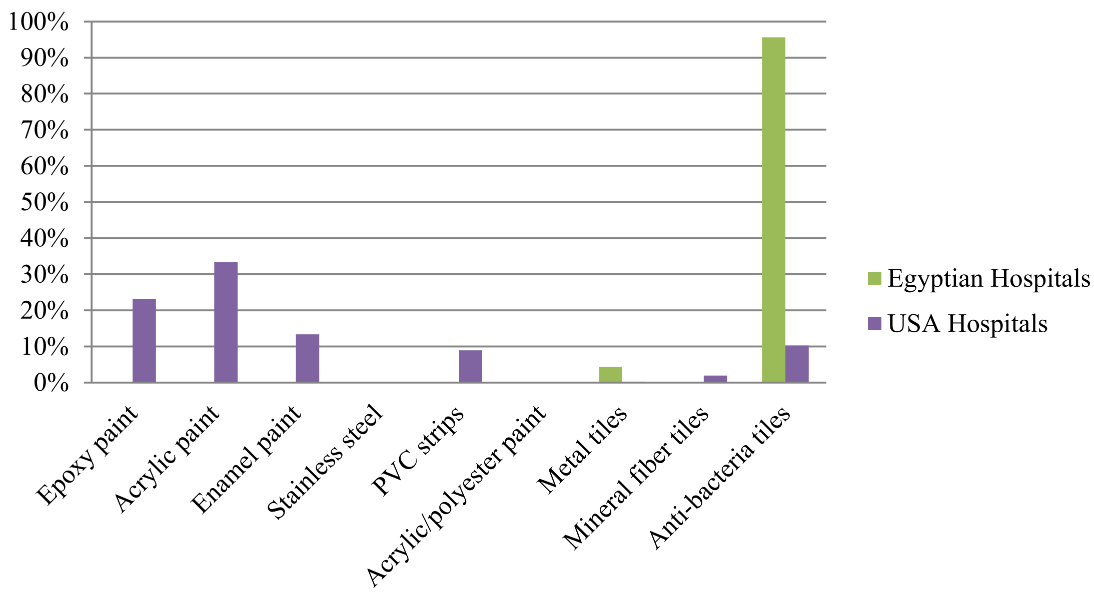


Figure 3: Frequency of ceiling finish materials use

It is interesting to note that the current selection of OR ceiling finishes in the USA concurs more with those adopted in Egypt during the 1990s. The study by Shafie et al (1997) reported that emulsion paint was used in the majority of the surveyed ORs (50%);

and paints better satisfy infection control requirements of reducing the amount of joints to the minimum. It seems that current Egyptian hospital designers were more concerned with ease of maintenance by selecting the tile types of ceiling finishes despite the resultant harmful joints.

**Performance of the finish materials used in the USA operating rooms:**
The following is a summary of the results of the views of the USA hospitals' facility managers in regards to the performance-in-use of the commonly used finish materials adopted in their hospitals.

**Performance of the floor finishes:**
Facility mangers agree with the decisions of the hospital designers in regards to floor finishes. Their overall satisfaction with the performance of sheet vinyl was highest that the other materials (3.9). When compared with the epoxy terrazzo floors, performance was viewed to be better, where epoxy terrazzo floors received an average evaluation of 3.4. Sheet vinyl was considered superior in all criteria except durability. The best viewed quality of sheet vinyl was sterile properties (figure: 4).

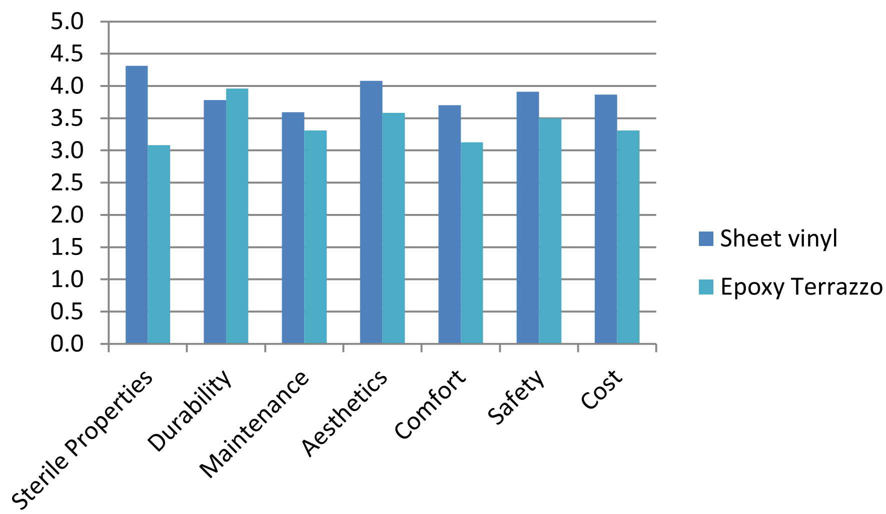


Figure 4: Performance of floor finish materials

**Performance of the wall finishes:**
The hospital facility managers are almost equally satisfied with the overall performance of the two commonly used wall finish materials (figure: 5). Their average evaluation was 3.9 for epoxy paint and 4.0 for wall covering with PVC, Corian and sheet vinyl.

However, they view the performance of the wall covering materials of PVC, Corian and sheet vinyl as superior in regards to sterile properties, durability, comfort, and safety. These are essential criteria in the performance of ORs. The more commonly used epoxy paint is viewed superior in regards to maintenance, aesthetics, and more importantly cost. This is probably the reason for selecting it in the majority of surveyed hospitals. This also concurs with the results of the facility managers' preferences survey in Texas (Lavy, 2012).

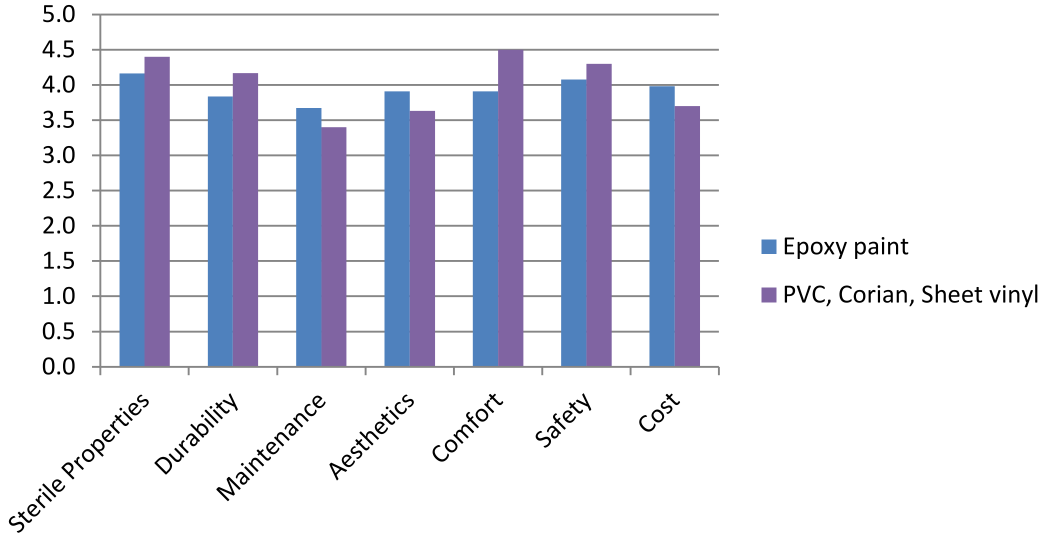


Figure 5: Performance of wall finish materials

**Performance of the ceiling finishes:**

Facility managers viewed the performance of the two commonly used materials as almost equal. Paints (acrylic, epoxy and enamel) received an average evaluation of 3.9, while the tiles (anti bacteria and metal) received an average evaluation of 4.0. It is worth noting that although the tiles are no longer accepted in the USA since they are not "jointless" their performance was rated as more superior than the paints in most of the performance evaluation categories: sterile properties, durability, maintenance, aesthetics and cost.

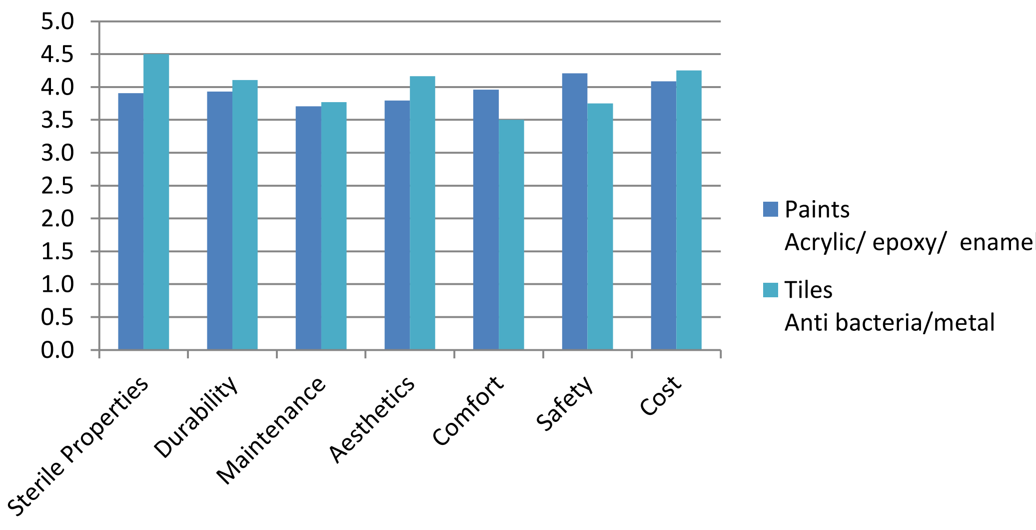


Figure 6: Performance of ceiling finish materials

## CONCLUSION

This study identified the materials that are most commonly used in finishing the operating rooms in Egypt and the USA. Sheet vinyl was the most popular floor finish material in both countries by a greet margin. Its performance in the USA hospitals was viewed by the facility managers to be more superior that the other floor finishing materials. It was considered superior in all criteria, especially in regards to sterile properties. The only exception was durability, where the performance of epoxy terrazzo floors was considered more successful.

Paints were used to finish the walls of the majority of the surveyed hospital in both countries. Epoxy paint was the most commonly used type. PVC/ Corian / vinyl wall coverings were the second distant used wall finish materials. Hospital facility managers were almost equally satisfied with the overall performance of these two wall finish material types. However, they view the performance of the wall covering materials of PVC, Corian and sheet vinyl as superior in regards to sterile properties, durability, comfort, and safety. These are essential criteria in the performance of ORs.

The materials selected for finishing the ceiling of the surveyed ORs varied dramatically between the Egyptian and the USA ORs. In Egypt, the ceilings were made of tiles of different types, while in the USA, it was dominated by paints. USA facility managers viewed the performance of these two material types as almost equal. However, they rated tiles as more superior than paints in most of the performance evaluation categories: sterile properties, durability, maintenance, aesthetics and cost.

Despite the drastic difference between the technical, economic and social conditions of Egypt and the USA, the selected finish materials were almost identical in both countries, with the exception of ceiling finishes. The distinctive requirements of this highly specialized space dictated the use of materials of high performance qualities especially in regards to sterile properties, durability, maintenance, aesthetics, comfort, safety and cost.

## ACKNOWLEDGEMENTS

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# MORTAR JOINT MAINTENANCE – FROM ABOMINATION TO PRESERVATION

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## ABSTRACT

The tools outlined in this paper show how inadequate repairs impact masonry performance and how good quality repairs can reduce unnecessary expenditure and increase the service life of masonry buildings. This discussion focuses on identification of poor quality mortar joint repairs, understanding what constitutes proper and improper repairs, and the structural ramifications of poor maintenance. The authors have combined structural and architectural engineering experience drawing from evaluation and repair work on hundreds of projects to generate the field research for this paper. The maintenance of mortar joints in existing structures is critical to the long-term durability of the masonry wall system. Unfortunately, the maintenance of mortar joints is often overlooked until irreversible damage to the walls has occurred and serious structural concerns arise. The masonry degradation process has several stages, which if identified early can avoid more costly and extensive future repairs. Professionals may have limited preservation expertise to identify poor quality repair techniques during assessments that assist in generation of repair plans. Proving the value and performance of mortar repair is critical in validating the quality and cost of work. The intent of this paper is to disseminate compiled practical knowledge for the reader to understand and be able to identify less than desirable methods of mortar joint maintenance, understand why poor quality mortar joints do not perform over the long-term, and see the steps required to implement good quality, long-term, mortar joint repointing.

## KEYWORDS

Mortar joints, maintenance, pointing, repointing, tuckpointing

## INTRODUCTION

Properly functioning mortar joints are vital in masonry walls. The mortar joints reduce the amount of water that infiltrates the wall, which allows the wall to dry between periods of rain. The outer surface of all masonry walls will experience water penetration when subjected to wind-driven rain. Masonry walls are not "waterproof" and are expected to absorb moisture, and then dry through evaporation. Some wall types accommodate large volumes of water penetration through the presence of properly designed and installed drainage systems including flashing and weep holes. The resistance to water penetration is dependent on materials, workmanship, design, and maintenance. Mortar joints are a primary component for water resistance in masonry walls and are considered deteriorated when they are cracked, eroded or weathered, have bond loss from the masonry unit, and displace out of the joint. Maintenance of mortar joints is often deferred, even though it is critical to wall integrity. Unmanaged and cyclic water penetration into masonry walls has a deleterious impact on the masonry, which is manifested in different ways and in stages from mild to severe. Although a variety of other conditions impact masonry wall performance and water resistance, this discussion focuses on the problems, maintenance, and repair of the mortar joints. When repairs are finally initiated, they can be short-sighted methods or of poor quality, instead of long-term properly executed repairs.

## IMPACT OF POOR MAINTENANCE

Water penetration of masonry walls manifests in various ways, from unremarkable to severe. Excessive water penetration of masonry will degrade masonry wall performance with respect to thermal conductivity, vapor and air permeability, durability, staining, corrosion of embedded metal, structural stability, and water leakage. Degradations that can be visually identified during an assessment are reviewed hereafter. Based on initial observations, exploratory probing to further evaluate the masonry may be justified. Mortar joints will typically show basic visual stages that are indicators of failure and the severity of the water penetration problem. The first stage has the mortar joints still sound, but some joint staining is evident indicating that moisture infiltration needs to be arrested. The second stage shows mortar displacing out of the joints. The third stage has even more mortar failure and displacement, in addition to more severe staining of the mortar and masonry with the accelerating water penetration.

### Leakage

The most intuitive and easily identified result of water penetration is interior leakage, whether it results in temporary water collection devices or simply stained interior finishes. Tracing the leak path from the interior back to the exterior often yields usable information as to the leak source. Interior leakage, a result of poor maintenance, is usually the primary reason that repair projects are initiated, due to its impact on building occupants.

Fig. 1. Heavy efflorescence form re-crystallized salts.

### Efflorescence

Powdery white efflorescence staining indicates water has cyclically infiltrated into the masonry wall, and solubilized salts within the masonry unit or mortar. As the water moves through the wall and evaporates at the interior or exterior of the wall, deposits are left behind on the face of the masonry as re-crystallization occurs (surface-efflorescence). This process causes expansion of the salt crystals that can cause damage to surrounding masonry. When the salts are trapped behind the masonry surface (sub-efflorescence), severe damage to the masonry can occur. In either case, constant water infiltration in masonry is detrimental. Light efflorescence that appears soon after construction, known as "new building bloom", occurs as well; however, this discussion focuses on heavy localized efflorescence (Fig. 1) that occurs due to excessive and uncontrolled water migration. The primary way to correct the staining is to stop the water from entering the wall at the source; a prime contributor is often failed mortar joints.

**Lime Deposits**

Stains associated with lime deposits typically are found as hard crusty streaks emanating from mortar joints (Fig. 2). Free lime (calcium hydroxide) is present in mortar as a by-product of cement hydration. As water infiltrates a masonry wall, the free lime is carried to the exterior wall surface where it reacts with atmospheric carbon dioxide to form limestone (calcium carbonate). Unchecked, staining can continue to build and cause masonry damage and deposits that are very difficult to clean.

Fig. 2. Lime deposits on the masonry surface resulting from water infiltration.

**Plant Growth**

Plant growth in mortar joints will thrive once the joints begin to fail, open up, and stay saturated (Fig. 3). An often overlooked mortar joint maintenance item is removal of higher plant growth. Uncontrolled, the growth will continue to grow, attach deeper into the mortar joints, hold moisture in the mortar, and accelerate deterioration of the masonry. Care should be exercised to limit any damage to the mortar joints during growth removal. Although sometimes plant growth is desirable for aesthetic reasons, it reduces the service life of mortar joints and makes maintenance difficult.

Fig. 3. Excessive plant growth contributing to mortar joint deterioration.

**Bond Loss**

Loss of bond between masonry unit and mortar causes significant damage in walls. Contributors to bond loss are freeze-thaw damage and associated mortar joint erosion (Fig. 4), which occurs when water entrapped in the assembly expands when it freezes. The freeze-thaw action creates micro fractures within the masonry that allows for increased water penetration. As the masonry becomes more porous and the deterioration from the freeze-thaw cycling increases on an exponential scale, the initial bond between parent masonry and mortar is lost.

Fig. 4. Mortar joint erosion.

Fig. 5. Unstable masonry areas as a result of mortar joint bond loss.

**Unsound Masonry**

Once the individual bricks lose the mortar joint bond they no longer behave as a cohesive monolithic unit. The overall section properties of the masonry walls are significantly reduced as well as the compressive strengths and resistance to buckling. The ability for water infiltration to increase rises dramatically, and the masonry walls and sections can become unstable (Fig. 5), dislodge, and potentially fall to the ground.

**Corrosion of Embedded Steel**

Embedded structural steel that is encased in masonry, especially from early Twentieth Century transitional buildings constructed between the mass masonry and curtainwall eras, is subject to corrosion and failure from excessive water infiltration. Curtainwall systems also rely on steel ties to provide stability for the masonry veneers. The ties are needed to resist lateral forces for both wind and seismic, as well as provide stability for the buckling forces due to the compressive loads. Many curtainwall systems also include steel stud backup members, which if not properly waterproofed can experience significant corrosion due to water infiltration. Corrosion threatens any ferrous metal component, particularly where in direct contact with adjacent masonry. In the presence of water, steel will corrode and expand with significant pressure due to the exfoliating rust layers. The pressure generated produces stress in adjacent materials (oxide jacking), and in many building assemblies, can cause severe damage.

**Structural Failure**

The deterioration of the masonry wall as well as the corrosion of the embedded steel components can lead to structural instability of the wall and portions of the masonry veneer (Fig. 6). Due to the fact that they are hidden from view, the corrosion of embedded structural steel and steel ties can continue unchecked for many years. The failures that occur from this deterioration often come without warning and can be catastrophic in the damage and injury that

Fig. 6. Out of plane masonry displacement.

is caused. The proper maintenance of masonry walls and use of quality repair techniques can greatly reduce the possibility of structural deterioration and failure and avoid costly structural repairs in the future.

## POOR QUALITY REPAIRS

Without the proper expertise in mortar joint repair, a host of methods and techniques may be utilized that provide minimal long-term benefit for the maintenance of the masonry and building.

**Improper Preparation**
Common mistakes associated with improper joint preparation are as follows. Damage to bricks by grinding, sawing or chipping may occur if the restoration mason is not experienced in this specialty work (Fig. 7). Mortar should be completely removed from the host masonry without leaving offcuts (usually a result of saw-cutting down the middle of the joint and doing no further removal). Mortar sections that are not completely removed at the intersection of the head and bed joints permit inadequate preparation depth to occur. Overcutting of the joints will reduce the size of the original masonry unit and increase the size of the mortar joints creating appearance issues.

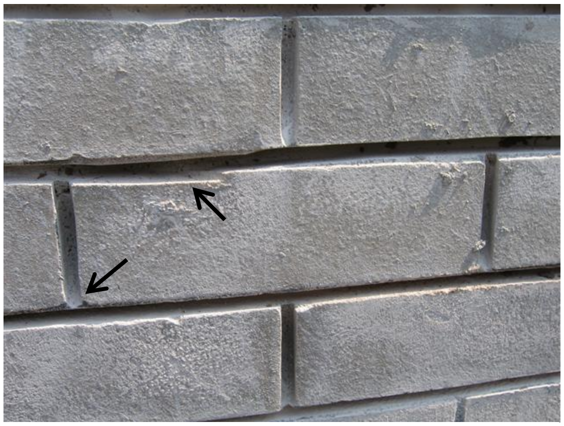

Fig. 7. Localized brick damage and partial mortar removal due to inadequate preparation.

**Excessively Hard Mortar**
Pointing projects completed with overly hard mortars (high compressive strength relative to the parent masonry) result in cracking and spalling of the masonry units as differential movement occurs between the materials. In particular the outer faces of the brick will chip and spall from the higher compressive resistance at the outer face due to the repointing process (Fig. 8). Any replacement mortar must be sacrificial and work to compliment the brick.

Fig. 8. Brick face spalling resulting from placement of excessively hard mortar.

**Spot Repointing**
Multiple generations (in type of mortar and installation date) of random spot-pointing (Fig. 9) of mortar joints provides minimal overall wall performance improvement.

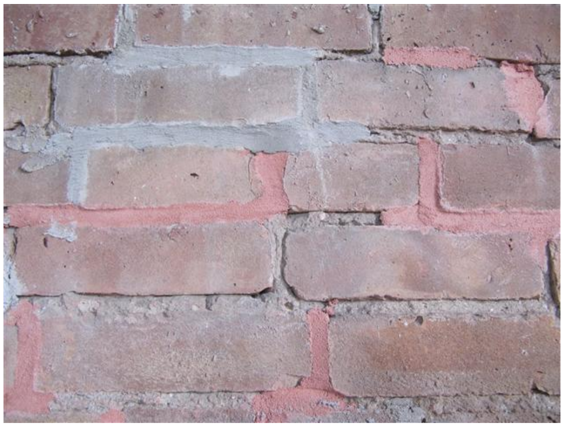

Fig. 9. Multiple generations of mortar joint repointing.

New bond lines and potential water infiltration locations are opened up at the junction of new and old mortar as each spot-point area is cut into the wall. Quantity control and identification of the joints to be replaced becomes difficult. In the NPS Technical Preservation Services' brief on Repointing Mortar Joints in Historic Masonry Buildings, it is indicated "…if 25 to 50 percent or more of a wall needs to be repointed, repointing the entire wall may be more cost effective than spot repointing. Total repointing may also be more sensible when access is difficult, requiring the erection of expensive access."

**Grout Bag**

Mortar installation with a grout bag consists of packing a loose mortar mix into a grout bag that is then squeezed out by hand through a narrowing nozzle into the mortar joints, the excess is scraped off and the joint tooled (Fig. 10). This application is found in new construction installation of interior/exterior thin masonry veneer, but does not lend itself to acceptable remedial repointing. A typical problem with this procedure is the mortar is mixed too wet, which increases the amount of drying shrinkage cracks (Fig. 11) that occur. Since the mortar is being squeezed into the joint, it is applied in one application instead of the recommended multiple lifts to achieve adequate compaction and bond.

Fig. 10. Grout bag installation of mortar yields poor results.

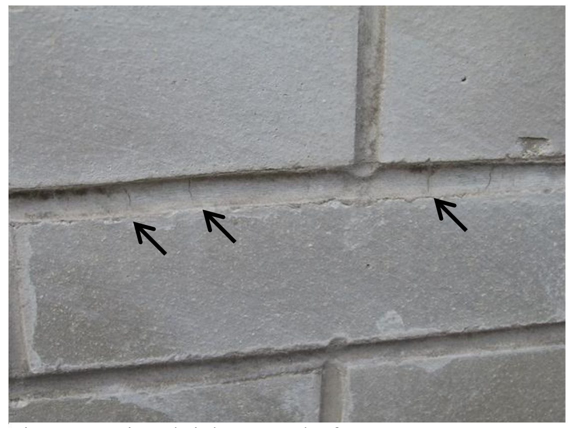

Fig. 11. Drying shrinkage cracks from too wet mortar.

**Shell Pointing**

Shell pointing is when a thin layer of new mortar is placed into the mortar joint. A thin joint does not promote long-term performance of the mortar and will allow a higher rate of water infiltration into the exterior wall. Typically, the existing mortar joint receives little or no preparation or mortar removal, and a single lift of mortar is applied to fill the joint to the surface of the brick (Fig. 12). Not only does this method not perform over time, but it changes the appearance of the masonry making the mortar joints more prominent.

Fig. 12. Thinly applied mortar over existing mortar will result in poor performance.

**Mask and Grout**

Masking and grouting consists of applying masking tape onto the brick faces leaving the mortar joints exposed and applying a thin grout layer to the joints working it into the surface. Crisp rectangular edges at the brick are a tell-tale sign this method has been used (Fig. 13). Mask and grout may unify the appearance of the wall and provide some crack filling capability, but this technique is not effective where long-term performance is required. Failure of this method occurs when the grout is applied to failed joints that require proper removal and replacement, and the outer hard shell of new grout fails and falls away from the inner deteriorated mortar. Aesthetically, this method will alter the mortar joint profile and also change the perceived size of the brick. Grouting is a lower-cost alternative to repointing and is frequently used in situations where it will provide little or no benefit.


Fig. 13. Failure of grout installed over deteriorated mortar joints.

**Sponge Grouting**

The sponge grouting technique (Fig. 14) is typically as follows: pressure wash the wall, sponge a thin layer of cementitious grout into the mortar joints, and sponge the bricks clean. The method is only effective on smooth surface brick that will allow for grout cleaning at completion. The grouting is often completed over moisture saturated and deteriorated mortar joints with minimal preparation to remove failed mortar or achieve uniform depth. Sponge grouting is not recommended because it is not as effective in reducing water penetration as proper repointing. Accepted industry practice no longer supports joint sponge grouting as a viable option for long-term repair when the joints have more than hairline cracking.


Fig. 14. Thin layer of grout applied to the masonry surface.

**Sandblasting**

The use of sandblasting for masonry cleaning and mortar joint preparation has been observed (Fig. 15). The loss of the fired surface exposes the softer porous brick interior and needs to remain; blasting it will affect appearance and damage the weather protective outer surface. The softer clay beneath the fired exterior will allow water infiltration to accelerate deterioration. Blasting will also increase the potential for


Fig. 15. Sandblasting removed the fired brick exterior surface.

the brick to remain dirty and promote organic growth.

**Sealant Overlay**

Cracked and open mortar joints are often a tempting invitation for inexperienced on-site personnel at buildings to fill with flexible sealant. This method is a cheap quick fix and easily implemented by maintenance staff that has minimal experience with proper masonry repair. This approach does little for the performance of the masonry. Sealant does not have the same life cycle as mortar and will prematurely fail and re-expose the wall opening (Fig. 16). The sealant will also trap moisture within the masonry (Fig. 17) inhibiting the evaporative drying process and cause premature failure.

Fig. 16. Sealant applied over failed mortar joints.

Fig. 17. Sealant application traps moisture within the masonry.

**Stucco Overlay**

Original stone and brick can be clad entirely with multiple layers of stucco, which is directly applied to the original masonry surface. Typical reasons include: aesthetics, water infiltration issues, deficient brick and mortar, or overall substandard masonry conditions. Stucco can be successful with proper substrate preparation and application, but often the stucco will only conceal deficiencies and deterioration of the host structure, and moreover cause accelerated deterioration. The overriding problem with stucco is that this hard exterior "shell" will tend to allow moisture behind the stucco (primarily at areas of deterioration) and will continue to impede drying and deteriorate the masonry from within. Irregular crack patterns and bulges are an indicator of stucco overlay failure (Fig. 18). "Brick-face" stucco is the process of applying three coats of stucco over top the given substrate. The first coat to be applied is the base or scratch coat, in which deep scratches are installed in the stucco to promote bonding with the subsequent coat. The base coat is then allowed to cure. The second or mortar coat is applied over the scratch coat, which will simulate the mortar joints. Simultaneously, the third and final brick coat is then installed. Mortar joints are then immediately cut through the third coat

Fig. 18. Outer layers of cracked stucco overlay removed exposing underlying masonry.

and slightly exposing the second coat, which creates the mortar and brick coloring effect. As the stucco de-bonds from the substrate, the area behind the stucco becomes an unintended drainage plane for infiltrated water and changes the water management strategy of the wall.

## QUALITY REPOINTING

Once it has been established that repointing is required, several steps need to be taken to ensure a quality long-term repair is completed. Additionally, mortar joints are just one contributor to water infiltration in building walls; flashings, copings, roof interfaces, windows, etc. need to be reviewed and deficiencies corrected as part of an overall building envelope solution. The intent of this section is to outline the key components in the mortar joint repointing process. Quality guidance for mortar selection, mix selection, and other related items already exists in BIA Technical Notes on Brick Construction "Maintenance of Brick Masonry" and the NPS Preservation Brief 2 "Repointing Mortar Joints in Historic Masonry Buildings". The procedure includes deteriorated mortar removal to a depth of approximately 2-2½ times the joint width, which is done by both saws/grinders (Fig 19) and hand chisels. Unfortunately, this process generates noise, dust, and debris when properly executed. Marginal success with dust reduction technology can be achieved if it is built into the project budget at the onset. Mortar must be removed to the edges of the masonry unit without damage. The mortar at the intersection of the heads and bed joints must also be completely removed to uniform depth matching the remaining areas, which is accomplished by hand or by die grinder. Power cutting should only be executed by skilled craftsmen or damage could occur to original masonry units. After initial desired depth of mortar removal is completed, deeper voids could be discovered that require deep repointing (back pointing) to fill before the standard repointing process is started. Not filling these voids could promote inner wall water paths or unsound masonry in the future. The masonry should then be washed down, and the masonry dampened before the mortar placement process. Install new mortar (Fig. 20) applied in multiple layers/lifts (typically 2-3 depending on the depth) as each previous layer becomes "thumbprint" hard. Compacting mortar in the joints in multiple lifts ensures good bond with adjacent masonry surfaces, good bond within the mortar, and minimal drying shrinkage

Fig 19. Part of the mortar joint removal process.

Fig. 20. Placement of new mortar in multiple lifts.

cracks because of the smaller sections. When the mortar has suitably cured (not excessively wet or dry), the joint is tooled to the approved joint profile to press the mortar firmly into the joints. Brushing the joint down after tooling removes the overly smooth and new look and exposes aggregate for a more appropriate appearance. Depending on the mortar mix design and temperature, humidity, and wind; the wall may require misting, wet burlap covering or other means for moist cure to limit drying shrinkage cracks. After the mortar has cured for several days, a final wash down to remove excess mortar and smears should be completed to give a finished appearance.

## SUMMARY

The masonry degradation process has several stages, which if identified early can avoid more costly and extensive future repairs. The use of the poor quality repairs, whether deliberately or un-intended, causes owners unnecessary expenditure and does little for the long-term performance of the masonry wall. These misguided maintenance methods often only conceal underlying deficiencies that will resurface later. Being able to correctly identify these less desirable methods during assessment will assist in accurate repair recommendations and plans. Understanding the simple steps in quality repointing and the resources available to achieve a preservation-level project and validate success will satisfy the needs of both designer and owner. Quantitatively proving the value of repointing is possible through field testing of masonry walls, as outlined in ASTM C1601 “Standard Test Method for Field Determination of Water Penetration of Masonry Wall Surfaces” supplemented with ASTM STP “Applying C1601-06 “Standard Test Method for Field Determination of Water Penetration of Masonry Wall Surfaces”. To ensure masonry failure is detected before more severe conditions develop, have an experienced professional perform periodic condition assessments of the building envelope approximately every 5 years to assist in early detection of deterioration and to assess the façade condition. Anticipate some level of masonry maintenance approximately every 10-20 years for repointing, façade cleaning, and sealant replacement. Masonry façades require maintenance to properly perform, limit leaks, and minimize extensive irreversible repairs. The awareness and use of the practical knowledge within this document is a valuable tool in the assessment and repair of existing buildings.

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# Pre-Occupancy Evaluation of High-Rise Building Forms

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## Abstract

The process of designing high rise buildings is demanding. In addition to being technically complex, high rise buildings must respond to the functional and psychological needs of the building users. As with other complex building types, an adequate design process suggests looking backward and forward simultaneously. Utilizing feedback from past users and projecting into the future are critical techniques when producing a successful building product.

What are the psychological differences between forms generated by formula and regular forms in high rise building? How can high rise buildings forms affect its environment, and people's attitude? What is the relationship between people's preferences and parametric high rise building form? This research attempts to answer these questions. Nowadays, architects are using **BIM** (building information modeling) in designing high-rise buildings, especially where BIM design tools can reduce design errors significantly. In addition, generating the forms through scripting with BIM tools is used for the form design of high rise buildings. What remain to be addressed is the psychological effects of generating high rise building forms digitally. In fact, this research can be considered as a pre-occupancy evaluation. Three groups of individuals were asked to participate in this survey. Individuals who were living in small cities, individuals who were living in big cities, but not in the downtown area, and individuals who were living in the downtown of big cities comprised the three groups. Different simulated high-rise building forms were demonstrated on the BIM Cave (a three dimensional room located in College of Architecture, Texas A&M University) for these three groups.

The quantitative data generated indicates that individuals who have the experience of living in the high rise urban areas strongly support generating forms digitally in comparison with individuals who do not have the experience of living in the downtown of big cities. In general, the results suggest that designers should consider generating high rise buildings form digitally, especially where parametric design combines modularity with rhythm in the high rise building skin, in order to meet the needs of future users of their designs.

**Kew Words:** Building Information Modeling (BIM); High-Rise Building; Parametric Design; Pre-Occupancy Evaluation.

## Introduction

Being technically complex, high-rise buildings must respond to the functional and psychological needs of the building users. As with other complex building types, an adequate design process suggests looking backward and forward simultaneously. Utilizing feedback from past users and projecting into the future are critical techniques when producing a successful building product.

The increasing number of high-rise buildings over the last fifty years makes it more crucial to have further analyses about their psychological effects. Over the past 30 years, the balance has shifted; in 1980, 80 percent of the high-rise buildings of the world were in North America but by 2010 the vast majority, 70 per cent, were in Asia, the Middle East and Africa (CBTU, 2008). Generating the form of a high-rise building has some psychological effects on peoples' behavior who perceive the buildings through walking in virtual pathways. Form variables can affect peoples' behavior by reducing stress, encouraging them to walk more, and helping them in way-finding.

Early research concluded that high-rises are, on balance, not advantageous for residents (e.g., Angrist, 1974; Cappon, 1972; Conway, 1977). At the societal level, they are accused of burdening existing services and infrastructure, worsening traffic problems, and damaging the character of neighborhoods (Broyer, 2002). In one of these studies

(Haber, 1977), 31% of three hundred undergraduate students reported that they disliked heights, and 22% felt stress in walking toward a high-rise building. Architects can affect peoples' perception of high-rise buildings through controlling the psychological effects of architectural form variables.

This study aims to understand the psychological effects of virtual form generation of high-rise buildings on human behavior. It attempts to provide a coherent parametric model of the different variables related to the form of a high-rise building. Although people infer connotative meaning from stylistic content, meaning may vary with experience and the context (Nasar, 1984). For instance, psychologists found that the human perceptual system perceives visual elements differently based on their distance and angle (Wagner, 2006).

## Parametric design

In the parametric architecture, designer use parameters to control shape. Through giving different value to the architecture parameters, various objects can be generated. Equations can be used to illustrate the linkages between configurations, therefore defining an associative geometry, i.e. the "constituent geometry that is mutually linked" (Burry 1999). That way, interdependencies between objects can be established, and objects' behavior under transformations defined. As observed by Burry (1999), "the ability to define, determine and reconfigure geometrical relationships is of particular value." In addition, parametric architecture often involves a technological, algorithmic explanation of geometry (Kolarevic, 2009). In HSB Turning Torso Building, Santiago Calatrava has designed a parametric model (Figure 1). The form could be generated from mathematical formula, and some vertex in the Revit could start the form. Afterward, architecture parameters could be defined and correlated through a mathematical formula. The final generated form has some changeable variables that are linked with each other.

**Figure 1.** HSB Turning Torso, Designed by Calatrava

## Research Method

Regarding this research question, which seeks to understand the psychological effects of high-rise buildings' forms on people's behavior, the major material of the study would be on how people perceive a high-rise parametric model. To address this question, we need to know people's perception procedure, the relationship between human behavior and built environment, and the significant variables in form generation of high-rise buildings.

To recognize the significant variables in the form generation of high-rise buildings, a parametric model of a high-rise building in a virtual world has been designed. Modularity, rhythm, color, material, shape, and balance of horizontal and vertical line will be considered as the form variables in this parametric model. The high-rise parametric model, as the independent variable of this research, can be considered as a possible origin of people's satisfaction. Built environment is the mediator variable which represents the mechanism through which the high-rise parametric model (predictor variable) affects the people's satisfaction (dependent variable). On the other hand, people's preferences before building a high-rise construction is the moderator variable, which is a variable that affects the direction and strength of the relationship between the high-rise parametric model (predictor variable) and the people's satisfaction (dependent variable). The conceptual model in this research configures two hypotheses which are categorized in different groups of pre-occupancy evaluation and post-occupancy evaluation. As shown in the figure 1, the hypothesis one happened when people's preferences contribute in configuring a new built environment which is a high-rise building in this study. Hypothesis one argues that analyzing people's behaviors in virtual world can suggest the degree of complexity for each architectural form variable to designers. The main concept in this hypothesis is to evaluate the generated forms by each individual with regard to his or her reactions in the virtual sphere.

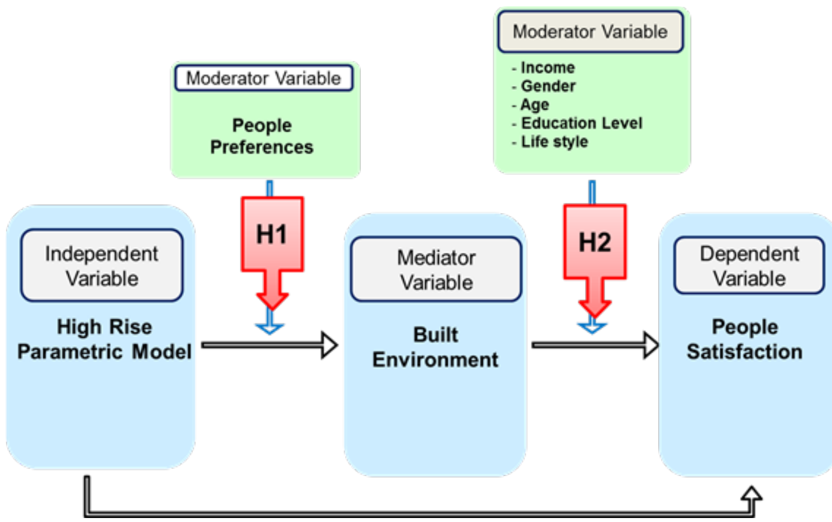


**Figure 2.** H1 (Hypothesis 1), H2 (Hypothesis 2) in conceptual model

In the post-occupancy evaluations (POEs) phase, after configuring a high-rise building, the people's satisfaction can be evaluated. As shown in the figure 1, the hypothesis two happened when people's characteristic variables such as gender, income, age, educational level, and life style contribute in evaluating a high-rise built environment. Hypothesis two argues that people's background (lifestyle) can affect satisfactory of people with the architectural forms.

**1. Pre-Occupancy Evaluation:** Pre-occupancy evaluations supply information about the building itself prior to the occupancy. It will be used for testing hypothesis one in this research. A parametric model which included all form's variables is used in this phase. These variables should be correlated with each other's. On the other hand, this smart parametric model should have user friendly interfaces that enable people to generate their own desired forms. Three sets of individuals are asked to participate. People who are living in small cities, the downtown of big cities, and suburb of big cities are shaped these three groups. Individuals try to find their arbitrary high-rise building form in BIM (Building Information Modeling) Cave. BIM Cave is a darkened room in Texas A&M's

Langford Architecture Center (2011), that Building Information Modeling software can be navigated through the bowels of a virtual building while visually immersed amid an array of 12-display monitors.

**Figure 3.** BIM (Building Information Modeling) Cave, Texas A&M University, College Station, TX

This facility allows viewers to submerge themselves in multi-screen BIM simulations motorized by three powerful computers using standard BIM software, such as Revit. The survey consists of the observation and self-reported processes, in which individuals from three groups will experience in the BIM Cave. A very quick tutorial will help people to make themselves familiar with this room and software. Afterward, they will evaluate all the forms variables in a high-rise building model. Each of these variables ranges in ten degrees of complexity. Individuals will select variables, and their arbitrary degrees. Finally, they will fill an online questionnaire about their own design.

**2. Post-Occupancy Evaluations (POEs):** Post-occupancy evaluations (POEs) are building studies that attempt to distinguish the successes and failures of design results. Evaluations can be recognized from other research sorts by their classification as field studies. Unfortunately, they do not fail efficiently into other traditional research subcategories. They vary from studies specifically focused on the analysis of particular buildings (case studies) to issue-focused studies that happen to occur in existing buildings (Shepley, 1996). This method will be used in testing hypothesis two. In this part of research, an existing high-rise building, which is approximately similar to the results of hypothesis one, will be used. Again, three groups like pre-occupancy evaluation research will be asked to fill questionnaires after walking outdoor of the specific high-rise building.

## Conclusion

This is one of the first studies of pre-occupancy evaluation in form generation of buildings, using parametric modeling. The finding from this exploratory study may suggest that evaluating people preference through virtual sphere enhances form generation process. This study encourages designers to use pre-occupancy evaluation before generating high-rise building forms, especially where some architecture variables such as modularity and rhythm are concerned.

## Expectations & Limitations

The present study has certain limitations that need to be occupied into account when taking into consideration the study and its aids. Some of these limitations that are mentioned below can be seen as productive avenues for future research under the same theme:

- The BIM (Building Information Modeling) Cave that will be used in the method is completely new, and the validity and reliability is unknown.
- Using same groups in pre occupancy evaluation and post occupancy evaluations (POEs) is problematic, especially where the BIM Cave is located in Texas A&M University and users of downtowns are living in different cities.
- The study sample was limited to three groups which might limit the generalizability of the findings.
- There are some unexpected architectural forms that cannot be organized in measurable categories. Although there are so few in the cities, they can be considered as a limitation of this research.

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# Process Management Approach for Achieving Total Building Performance: Essential Requirements for Sustainable Construction

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## ABSTRACT

The clamour for sustainable buildings in the construction industry is on the rise. Sustainable buildings reduce building energy consumption, support health, comfort, and wellbeing of building inhabitants without compromising the wellbeing of the earth. Studies have also shown that sustainable buildings make money sense. However, issues relating to process of achieving sustainable buildings goals have not been receiving the attention it requires. Process management is an essential tool which most architecture, engineering, and construction (AEC) professionals overlook or do not pay much attention to. If the process is wrong or inadequate, sustainable buildings goals may not be achieved effectively, if achieved at all. This may have significant impacts on future acceptance of sustainable building practices. With the use of existing data in the literature and our research in this field, this paper proposes a holistic approach for achieving the intended benefits of sustainable construction.

**Keywords:** Integrated design process; Process management; Project management; Sustainable construction delivery; Total Building Performance

## 1. INTRODUCTION

Sustainable construction, when done appropriately, has economic, social, and environmental benefits. Integration of these benefits will help address the need for sustainability which includes: global environmental crisis, rapid growth of economic activity and human population, depletion of natural resources, damage to ecosystems and loss of biodiversity, human health, comfort, and performance and productivity in indoor environment. Achieving clients' satisfactions has been recognized as one of the most significant challenges confronting the construction industry (Bubshait, 1994; Kometa et al. 1995). This has become more important in the 21st century with construction clients now demanding sustainable construction as a key performance indicator in their projects. To help architecture, engineering, and construction (AEC) professionals realize the goals of sustainable buildings, non-governmental rating schemes such as LEED (US), Urban Planning Council (UAE), and BREEAM (UK) have developed specific assessment standards and criteria. Such standards are expected to aid decision makers at design and construction stage to achieve specific sustainable construction performance levels.

Clients of the construction industry have been demanding a shift from traditional perspective approaches to performance based approach procurement. Hartkopf et al. (1986) recommended a performance based approach to building construction delivery rather than building construction that is prescriptive based. Prescriptive approach defines standard or regulatory requirements in rigid terms, without questioning the relevance of specified limits while performance-based approach ensures proposed design meets defined construction goals rather than prescribing solutions. Performance based approach allows multidisciplinary construction design teams to produce alternative designs which are more flexible, rational, innovative, as well as cost effective. This approach is otherwise known as Total Building Performance (TBP) approach. TBP approach requires AEC professionals to take conscious consideration of implications and synergistic effects of the various building performance mandates. Though, TBP concept provides technical know-how required to produce sustainable buildings, the process of achieving sustainable building goals still needs further improvement. Construction process management (CPM) is an essential and holistic management approach which can be used for this purpose. However, CPM is often overlooked in the management of construction projects. Communications among multidisciplinary professionals and logistics for sustainable building delivery are essential to CPM success. If communications among multidisciplinary professionals and the required logistics for sustainable building delivery are poorly managed, sustainable building goals may not be achieved. Failure to deliver sustainable buildings required by the clients may have significant impacts on future acceptance of sustainable building practices.

The aim of this paper is to demonstrate, using explanatory method, the importance of CPM in achieving sustainable buildings with high performance qualities. An explanatory study seeks to provide an explanation and report of a situation or a problem (Robson, 2002; Gray 2009; Fellow and Liu, 2008). Using this method, we discussed sustainable construction issues, TBP concept and construction process management (CPM). The research objective is to investigate the gaps in sustainable construction current practices and develop an integrated framework that will facilitate TBP from the perspective of CPM theory and sustainable construction. This study highlights the importance of CPM to improving sustainable construction practices.

## 2. SUSTAINABLE CONSTRUCTION ISSUES

Sustainable sites, water efficiency, energy and atmosphere, materials and resources, IEQ, innovation and design process, and regional priority are main sustainable technical information that must be addressed (Cheng 2010). If AEC professionals are not aware of how these criteria would influence their proposal to design and build a building, then sustainable goals set from the predesign stage will be compromised.

Any building exists within a site context. Two buildings may be the same in terms of design but their locations will influence their performance. Possible impacts of site on building performance should be understood and addressed effectively from the pre-design stage. Other considerations for sustainable site should consider the possibility of (but not limited to): re-using existing sites and/or building, having vegetation on site as much as possible, not polluting the site environment, protecting natural habitats, reducing light pollution, developing site features that control storm water, using existing facilities in the neighborhood, and reducing the use of automobile as much as possible. Development of efficient water technology that can reduce building water usage, both indoors and outdoors, without reducing the health, comfort and wellbeing of the users should be considered in effort to meet water efficiency requirement. With regards to energy and atmosphere, reduction of carbon emission to the atmosphere is the main motivation for reducing building energy consumption and developing clean energy alternatives. Building should be designed to save energy as much as possible without compromising human comfort. Measures should be taken to achieve energy efficient passive and active systems. Use of renewable energy systems should be promoted and should be well integrated with other building systems. To ensure maintenance and operation of building energy systems as intended and optimize energy performance, commissioning process of building energy systems that cut across building delivery stages should be given priority.

Materials and resources is another criteria required to be considered. Efficient use of materials and resources will improve the environment and prevent extinction of natural resources. Development of buildings with little or no considerations for IEQ will fail sustainable buildings criteria. Construction waste management, reduce, reuse, and recycled of building materials and resources, use of building materials with less environmental impacts, and certified environmentally responsible materials should be considered. When designing buildings to improve IEQ, indoor air quality, thermal comfort, acoustic comfort, light/visual comfort, and spatial comfort should be considered. For building to be performance based rather than just being prescriptive only (e.g. just following standards), it will require innovative ideas in addition to consideration for regional environmental priorities. Innovative construction requires integrated design and construction practices. For effective actualization of sustainable building design criteria, integrated design and construction practices should be adopted throughout building delivery stages. AEC professionals should also develop holistic means of evaluating building performance. TBP approach provides such knowledge. Though TBP concept is not a new idea, and there are case studies of building projects that have adopted TBP concept in their building delivery, its implementation in the industry is still very limited. This may be due to logistics and complex nature of TBP concept. Perhaps, this concern can be addressed if CPM is not neglected. Sections 3 and 4 discussed TBP and CPM concepts respectively.

## 3. TOTAL BUILDING PERFORMANCE (TBP) CONCEPT

The TBP concept was first developed by TBP research team from the Centre for building performance and diagnostics at Carnegie Mellon School of Architecture. Centre for total building performance (CTPB) at the National University of Singapore (NUS) further developed this concept with special focus on tropical region countries. TBP concept was introduced due to continuous failure of construction industry to meet construction clients' goals. The failures are due to fragmented building delivery process, non-optimal design, abortive construction works, inadequate communication among construction professionals, non-holistic decision-making process, in efficient energy, materials and resources consumption, poor IEQ, poor occupants and users' satisfaction which compromise building their well-being, performance and productivity. TBP vision is to provide a world class, high quality, competitive, energy conserving, easy maintenance, and design excellence buildings. Achieving TBP vision will require knowledgeable construction players. The professionals must be highly skilled, competitive, productive, be able to manage construction delivery process. TBP emphasizes on integrated design process and practices to deliver integrated, buildable, resource effective, safe buildings that adopt advance technology.

In order to deliver sustainable buildings required by clients, TBP process should be applied throughout building delivery stages (Oyedele et al. 2012). Figure 1 shows how TBP concept can be applied to building delivery stages. In the first phase of developing sustainable buildings with high performance, considerations must be given to integration within, between, and among building systems which include interior; envelope; mechanical, electrical and plumbing (MEP); and structural systems. The building systems must also be successfully integrated with outdoor environment. Integration must be done to realize performance mandates required to achieve sustainable buildings. These include: thermal performance, indoor air quality performance, acoustic performance, light/visual performance, spatial performance, and building integrity performance.

Thermal performance will address measures required to improve issues which include but not limited to air temperature, humidity, air velocity, radiant temperature. Indoor air quality performance will address measures required to reduce pollutants (chemical, biological, physical) concentrations. Acoustic performance will address measures required to improve issues which include but not limited to reverberation time, sound pressure level, and sound audibility. Visual/light performance will address measures required to improve issues which include but not limited to light levels (e.g. by integrating daylight and artificial light), contrast, colour rendition, and general visual appearance. Spatial performance will address measures required to improve issues which include but not limited to adjacencies, accessibility, way-finding, efficiency, and ergonomics. Building integrity will depend on how considerations for sustainable sites, water efficiency, energy and atmosphere, materials and resources were successfully taken into consideration when addressing performance mandates that are directly related to IEQ criteria. Ability of delivered buildings to resist degradation, structural movement, earthquake, chemical and biological attack fire occurrence, and ensure safety of building users in case of fire outbreak are other examples of factors that can determine successful building integrity.

Too often, sustainable construction practices focus a lot on saving the environment without much consideration for the primary purpose of constructing buildings, i.e. human. When designing buildings to fulfill sustainable criteria, human limits of acceptability of building performance mandates should be considered in order to improve their health, comfort, and wellbeing. Physiology, psychology, sociology, and economics are the four limits of human acceptability of building performance mandates (Hartkopf et al. 1986). Physical health, safety of building users, and basic bodily functions are examples of building occupants/users' physiological limit of building performance mandates acceptability. Psychological limit addresses mental condition (e.g. expectation due to knowledge and experience) of building users. Culture and religious expectation are examples of sociology limit. Ability to allocate resources in most efficient manner will affect economic acceptance.

Suitability, reliable (durability), and flexibility implications of the performance mandates as a function of the limits of acceptability should be considered. Consideration for suitability ensures decisions made meet sustainable construction criteria in the present and future. Consideration for reliability is important to ensure decision made will make building perform as intended throughout the life of the building, given appropriate maintenance and use. Consideration for flexibility ensures building accommodate changing functions and occupancies Without compromising performance criteria within the limits of acceptability.

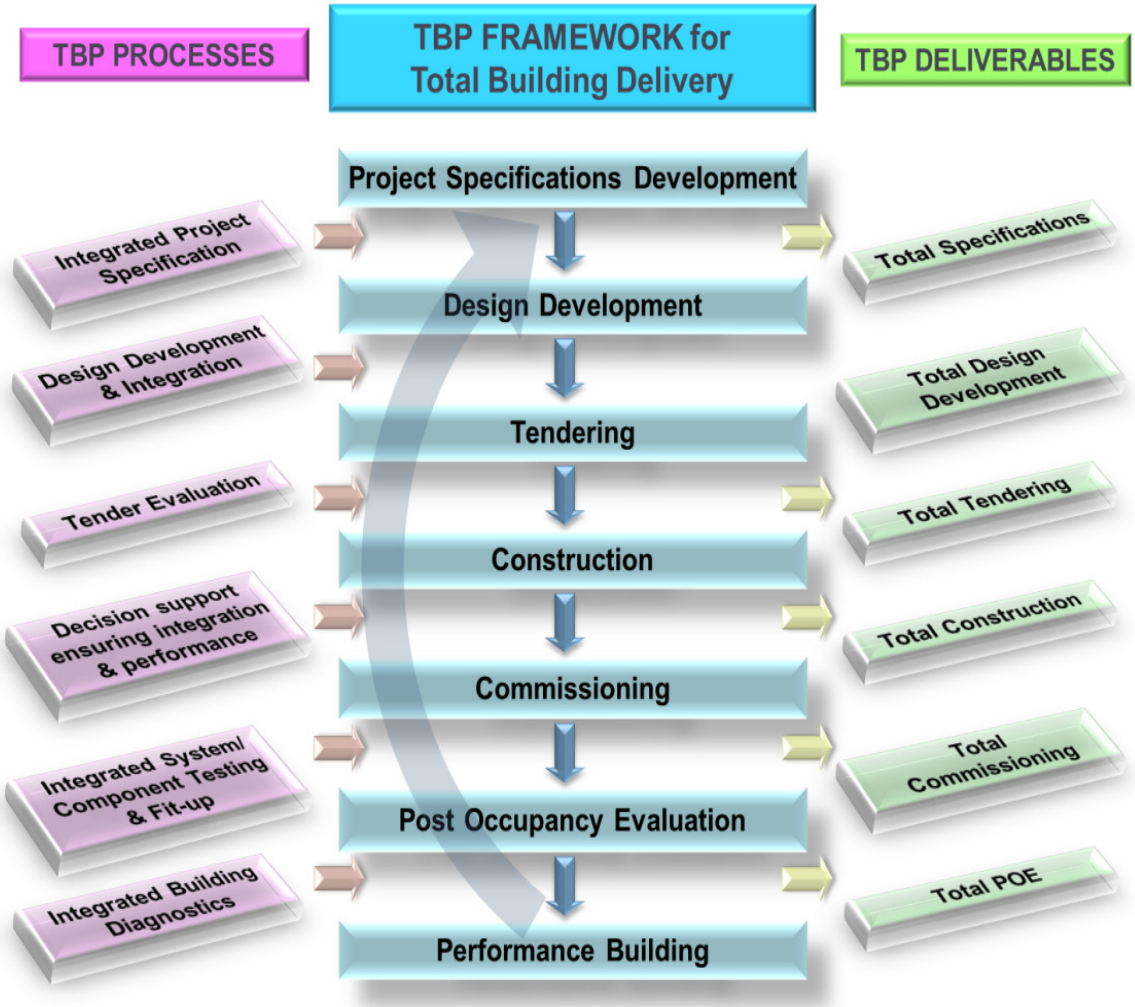


**Figure 1**: Application of total building performance (TBP) concept to building delivery (Oyedele et al. 2012). *Note: Commissioning process should start from project specification development stage and continues throughout the building delivery stages*

Design development and integration is the second phase of sustainable construction delivery. All issues considered in the first phase of sustainable construction delivery as mentioned above should be implemented in the second phase to achieve total design development. The third stage is tender evaluation. In order to achieve sustainable construction, sustainable tender process, commitment to performance based approach, and experts' feedback and decision should be adhered to effectively to achieve total tendering. The fourth stage is construction. This involves conformance to design, methods of materials selection and application, and methods of systems and components evaluation. Decisions made on all activities at this stage must adhere to integration and performance to achieve total construction. In addition to the commissioning process that should start from the pre-design stage and through the subsequent building delivering stages, commissioning of integrated system/components and fit-up must be carried out to achieve total commissioning that ensures building has being constructed as intended. During maintenance and operation of constructed building, post occupancy evaluation must be done to verify its suitability and reliability. Experiences gained from the completed and occupied building should be taken into consideration when developing other projects specifications.

The concept of TBP has been implemented in Singapore construction industry by CTPB research team at NUS. Their projects using TBP concept include: Singapore National Library building, Zero energy building at Building construction Authority (BCA) academy, Capital tower, Urban redevelopment authority centre, Khoo Teck Puat Hospital at Yishun area, and Jurong Town Cooperation (JTC) stack-up factory at Woodland. These projects have won numerous local and international design and construction awards such as green mark platinum award, green mark gold award, water efficient building award, energy efficient building award, construction excellence award and façade design, excellence merit award, Asian Architecture award, Fiabci Prix d'Excellance. These awards are from local and international organizations such as Building and Construction Authority of Singapore, Singapore Institute of Landscape Architects, Singapore Institute of Architects, Association of South East Asian Nations (ASEAN) centre for energy, the International Real Estate Federation (Federation Internationale des Administrateurs de Bien-Conselis Immobiliers- FIABCI). Despite evidences of sustainable design and construction benefits experienced from using TBP concept, application of TBP concept can still be improved further if CPM concept is integrated in TBP concept. Complexity of TBP concept and involvement of many AEC professionals and relevant specialists necessitate integration of process management into TBP concept for better performance. Section 4 introduced CPM concept. This was done for better appreciation of why CPM concept is important to TBP concept for better achievement of sustainable construction goals.

## 4. CONSTRUCTION PROCESS MANAGEMENT (CPM)

The term CPM discussed in this paper refers to process management across the different construction delivery stages, not just the on-site stage. This section will address the importance and application of process management knowledge, skills, tools and techniques for the management and integration of construction processes needed to achieve clients' sustainable construction requirements.

Managing construction processes is key aspect of project management. This means managing the planning and implementing systems and services including managing the project teams, information management (includes client requirements and decisions), change and knowledge management amongst others. Project management is not an easy task and Griffith (2011) emphasize that construction projects are complex and project managers are faced with the enormous challenge of efficiently and effectively managing the process. This is compounded by the ever increasing requirements demanded by the complex network of stakeholders and the need for delivering sustainable buildings. Project management is realized through the application and integration of the project management processes (i.e., initiating, planning, executing, monitoring and controlling, and closing) utilizing knowledge, skills, tools, and techniques to meet project requirements (The Project Management Institute, 2004). Forbes and Ahmed (2011) indicate that in the project environment, management's role is to stimulate and articulate unique networks of commitments between the stakeholders that form a project team. Describing and organizing the work of the project are the concerns of project management processes. Griffith (2011) identifies the following three key processes (i.e., core processes, support processes and assurance processes) organizations use to carry out their business and all are clearly within the total construction processes. History has shown that large and complex construction projects typically suffer from a lack of good project management practice (US DOT, 2000; Fraser, 2004). This result in project failures with long extended schedules, budget over run and sometimes the benefits not realized. In almost every industry, this problem has been reported (CIOB, 2011).

Often, the different construction processes are planned and executed independently of the individual companies involved, through autonomous teams, creating silos of processes. These silos processes need to be brought together in a collaborative work (CW) setup in order to share/exchange information across the supply chain during transactions and implementation of activities. Therefore, project managers must devise means of managing the collaboration to facilitate the work of distributed project team members. Erdogan et al. (2008) emphasize the need for CW in construction due to the nature of projects which are multi-organizational and geographically dispersed. Integration and Collaboration overcomes the fragmentation that has come to characterize the construction process (Egan, 2002; Forbes and Ahmed, 2011). Integration can facilitate the design and construction process and help deliver sustainable buildings. Process management approach has been applied in managing construction client requirements (Jallow, 2011). A similar thought on integrated design and project delivery, supported with development of integrated processes, which is within the concept of process management, has been suggested for energy efficient retrofit buildings (Lee et al., 2012; Parrish and Regnier, 2012). An integrated team includes the client, as well as all those involved in the delivery processes, who are pivotal in providing solutions that will meet client requirements; and requires team members to harness the potential of their integrated supply chains (Egan, 2002). A critical component of construction process management is the effective sharing and exchange of information across lifecycle phases and between project teams. This includes facilitation of collective decision-making and management of project requirements changes from a process management perspective (Jallow et al., 2009). This requires giving partners access to information or one partner transmits/shares information to/with another which has been facilitated by the internet and the fast advances in communication and information technologies coupled with global competition (Attaran and Attaran, 2007; Anumba and Ruikar, 2008). However, this is challenging as a result of the heterogeneous IT systems used in the different organizations, though several efforts are making progress towards solutions for interoperability to enable integration of processes and information flow and exchange (Anumba et al., 2008).

Process management is about planning, organizing, directing, leading, coordinating and controlling resources in order to achieve success. It includes the use of specific methods and tools (Rainer and Cegielski, 2011). Process, as a set of activities is central factor to process management. The application of 'process' discipline has received wide adoption by various organizations in project management, and is getting well established and acknowledged in the construction industry (Sun and Oza, 2008). Process management is relevant and can contribute to TBP. A major factor that contributes to the failure of meeting sustainability whilst achieving performance is the lack of transparency of the construction processes. In order to facilitate TBP, processes should be mapped out by modeling the activities of the design, construction, and maintenance and operations of building systems (interior; envelope; mechanical, electrical and plumbing (MEP); and structural systems) and outdoor environment systems, and project support processes. In this way, the activities become visualized, and project teams would be required to adopt and follow criteria for achieve high performance and sustainable building. It is essential that construction processes are harmonized in an integrated approach. This would require specifying and establishing a mechanism that will facilitate collaboration and interaction between the activities within, between, and among the systems. It is crucial for project teams to understand the precise interaction points they would be required to integrate and/or coordinate efforts for TBP during construction project delivery. In order to execute development projects successfully, factoring the different lifecycle phases of a project and the different processes and resources involved, teams and all other stakeholders have to work in unison and collaboratively; where integration, coordination, cooperation, and communication and information delivery has to be integrated within their activities and general project processes.

## 5. SUSTAINABLE CONSTRUCTION DELIVERY FRAMEWORK

Based on knowledge gained from sections 2 to 4, this subsection will identify and explain gaps in sustainable construction practices. The explanation will lead to the need for framework development. This section will propose a holistic approach required for achieving the intended benefits of sustainable construction as much as possible within the constraints of technology, knowledge, practices and policies.

Construction professional needs to understand issues to address, in particular TBP issues. These include: processes they are involved in; information they required to design performance based solutions; internal and external; managing changes relating to their processes and designs as well as changes to client requirements and performance achievement, and knowledge sharing and exchange between teams. In recognition of the challenges to deliver TBP and understanding potential approaches to deal with those challenges, this paper proposes an approach towards the development and implementation of TBP. The approach, '*an integrated sustainability construction delivery approach',* places emphasis on collaborative working, process management (*including integration between processes*), change and knowledge management and integration and interoperability of applications to facilitate information flow and exchange. This is aimed to support the management of construction processes across discipline boundaries and lifecycle phases that exist within projects. Integration is a key element of this approach and can help increase construction operational efficiency and effectiveness; provision of project-wide information to support decision making; facilitating access to knowledge and the management of changes. Non-holistic decision making can be supported through integration of processes with the inclusion of change management. This is important because decisions could impact other goals which would need to be analyzed. It will enable rapid responses to client changes and the inclusion of simulation and analytical tools to evaluate energy and sustainability parameters, and the overall building performance. Due to mounting concerns for environmental sustainability, sustainable supply chain management has to be factored within this approach. This would mean designing and implementing a sustainable supply chain for minimal environmental impact during the construction period. This is in line with sustainable building concept as it will help reduce environmental impact of buildings in cooperation with all stakeholders throughout the lifecycle. Because it is recognized that construction project teams operate their processes independently of one another, it is inherent that construction projects design and implement the *integrated sustainability construction delivery approach* so as to be better positioned and deliver TBP. This is realistic because all construction processes and activities, products, and services can be coordinated and controlled in a manner that promotes the economic, environmental, and social responsibilities that are inherent in the sustainable construction delivery.

Adoption of the integrated approach in sustainable construction projects will facilitate management of the processes required to ensure decisions made at the project specification stage of building delivery with regards to integration of building systems to fulfill building performance mandates within the limits of acceptability and terms of evaluation, are carried across the building delivery stages. Members of the project team must coordinate to minimize the expected energy and water usage of the buildings, improve occupants' health and comfort, and meet the owner's specific design goals required for achieving high performance buildings. The integrated approach utilizes an integrated construction process, where the owner, design team, engineers and other stakeholders contribute together to optimize total performance of the building as a whole rather than just the performance of individual system or service.

## 6. CONCLUSIONS

This paper provides practical knowledge required by AEC professionals in delivering building projects that effectively meet the needs of construction clients, owners, end users, and society/regulations. We envisaged that integration of CPM into TBP concept will improve quality of building projects delivered by construction professionals. This will facilitate future acceptance of sustainable construction practice. Initial efforts to develop a framework of the integrated sustainability construction delivery approach are in progress.

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# Building Science Integrated Systems Methodological Framework

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## ABSTRACT

Building performance is governed by physical processes, which are dynamically coupled in time and space, and whose degrees of interactions are often difficult to measure and appreciate. As a result, suboptimal performance and failures often occur. The goal of high-performance buildings is to optimize major aspects such as energy efficiency, life-cycle costs, and lighting, which are tightly coupled by the underlying physical processes. The premise behind this research project is that building integration/optimization can only be achieved when grounded on a shared understanding and communication of the underlying physical principles governing building performance, which can then enable the transformation of these principles into meaningful performance metrics.

This paper proposes a methodology for building systems integration through building science principles. At the core of the methodology, a vocabulary of building science concepts, principles, and metrics enables using existing knowledge to increase understanding and gain insights on the systems involved in a particular design (including degrees of coupling, redundancies, and behaviours), which in turn facilitates the creation of new knowledge that may be needed to integrate new systems and technologies. A set of generic building science rules implemented using systems theory will enable such knowledge creation while preserving systems integrity at all times.

The goal of this research is not to create a knowledge-base to replace building science professionals but to leverage an explicit vocabulary to increase understanding, learning, and communication of building performance for improved building integration. Furthermore, it is envisioned that the knowledge-base will serve as a bridge between building simulation, decision analysis, and optimization. This paper presents the initial attempt to organize a wealth of building science knowledge into a structured vocabulary. The power of generality and usability of the methodology will be tested with a case study.

The expected benefits of the approach are three-fold: 1) to promote a more systematic approach to optimize building systems, 2) to facilitate the integration of new systems and technologies in buildings, and 3) to improve the education and dissemination of building science knowledge for improved building integration.

## 1. Introduction

Building science (Building Physics in Europe) is still a fast evolving field that spans many disciplines. Over the last thirty years, building science research has gained momentum due to the increasing need to develop more sustainable buildings. Figure 1 (adapted from Mora et al. 2011) illustrates the challenges in assessing building performance, which at the core can only be overcome through the sound application of building science principles. Figure 1 illustrates building performance as having roots in service life, the economy, and the natural environment. All performance branches are connected in some way to the trunk (people) and dependent on it. The Figure emphasizes the central role of people in determining building performance (i.e. the fruits of the performance tree). Finally, the health of a tree depends on the climate (micro-climate) that surrounds it.

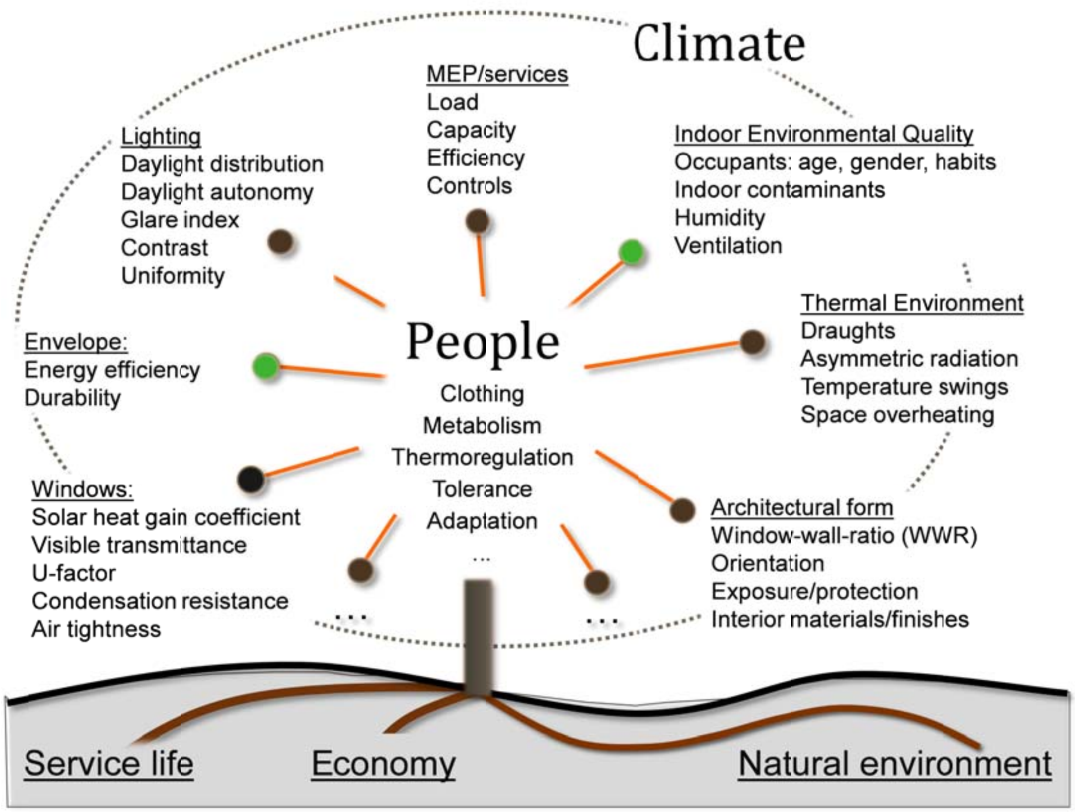


**Figure 1.** Building Performance Tree Analogy (Adapted from Mora et al. 2011)

A large amount research, driven in part by sustainability, has been published in reputable journals that relies on building science simulation (i.e. heat, air, and moisture transfer) to optimize various aspects of performance (e.g. energy, comfort, indoor air quality) under different climate and building conditions; as well as building science research focusing on durability. In practice, a common building science vocabulary is implicitly used by experts and knowledgeable building practitioners.

Despite the successes to improve energy efficiency, comfort, and durability of homes by programs that leverage on building science principles such Building America (DOE 2012) and efforts by leading organizations, such as the Building Science Corporation (BSC 2012), and research laboratories, such as ORNL (2012) and NREL (2012); the industry in general still has difficulties in understanding building science processes and transforming these into optimized building performance. To complicate matters, sophisticated computer simulation programs are becoming available that can be used by practitioners without knowledge of their underlying principles, assumptions, and limitations. Examples of these are BEopt (NREL 2012) for building energy optimization, WUFI (Fraunhofer 2012) for hygrothermal analysis of building envelopes and whole buildings, CFDesign (Autodesk 2012a) for building airflow simulations, Autodesk Multiphysics (Autodesk 2012b) for finite element modeling, and many others.

The main premise of this research is that even though each domain in the building industry has its own body of knowledge, there is still a lack of a common vocabulary to facilitate a shared understanding, communication, and application of cross-domain knowledge in practice. It is therefore hypothesized that building integration and optimization can only be achieved when grounded on a shared understanding and communication of the underlying physical principles governing building performance, which can then enable the transformation of these principles into meaningful performance metrics.

This paper proposes a knowledge-based methodology to guide building systems integration following a systems approach grounded on the principles of building science. The methodology uses an abstraction-refinement approach, well ingrained in design (Pahl et al. 2007), to help make complex problems tractable by the top-down and/or bottom-up materialization of solutions from incomplete problem formulations. Consequently, an also well-established generalization-specialization approach is used for knowledge representation (Booch 1994). At the core of the methodology, a vocabulary of building science concepts, principles, and metrics enables using existing knowledge to increase understanding and gain insights on the systems involved in a particular design (including degrees of coupling, redundancies, and behaviours), which in turn facilitates the creation of new knowledge that may be needed to integrate new systems and technologies. A set of generic building science rules implemented using systems theory will enable such knowledge creation while preserving systems integrity at all times. It is envisioned that the knowledge-based will serve as a bridge between building simulation, decision analysis, and optimization.

This paper presents the initial work to create such a knowledge-base that attempts to organize a wealth of building science knowledge into a structured vocabulary; vocabulary keywords are underlined and *italicized*. The paper is organized as follows. Section 2 describes the research methodology. Section 3 presents the higher level constructs of the proposed building science principles-based systems integration methodology. Section 4 discusses two case studies to demonstrate the potential application of the methodology. Section 5 analyzes its power of generality. Section 6 presents the conclusions and further work needed to develop the methodology to increasing levels of detail.

## 2. Research Methodology

This research project seeks to answer two fundamental questions: 1) what kind of generic building science is used to assist in building systems integration? How can this knowledge be represented to better assist in leveraging building science for problem solving, understanding, and communication?

Building science knowledge is scattered, and some is organized in ad hoc manner. This project uses a top-down methodological framework, which attempts to uncover high level patterns of concepts (i.e. high-level knowledge), and identify from these, lower level implementations. These high to low level concepts are then systematically organized into formal knowledge-based structures, called ontologies. Specifically, the research involves 1) Knowledge acquisition - Acquiring and selecting knowledge from the literature and practicing experts in the field, and 2) Knowledge representation - Organizing this knowledge into ontologies, and 3) proof-of-concept prototype implementation, testing and validation.

The knowledge acquisition process involves uncovering generic knowledge from different sources that can be re-used to assist in solving different types of building systems integration problems (e.g. design simulation, diagnosis, etc.). The knowledge acquisition process is case-study based. Case studies spanning different types of building science problems are selected and analyzed to uncover knowledge patterns, which are then used to develop a generic knowledge representation structure (i.e. ontology) to guide in problem solving. A proof-of-concept prototype will then be implemented as soon as a sufficiently complete branch in the ontology is obtained. The implementation will be then subject to evaluation and validation by experts in the field.

Following a top-down research approach involves first the development of a high level knowledge-structure called the upper ontology that needs to be tested for generality. Such ontology will in turn guide the development of sub-ontologies and their refinement into implementable knowledge structures. This paper introduces the upper ontology.

## 3. The Upper Ontology

The initial step in developing a knowledgebase is to create a representation of the problem space in which the exploration of solutions can take place. The challenge in developing such a representation is that it should only include the features that are relevant to the particular problem at hand (Simon 1999). Such a representation is called ontology: *"A* *domain ontology is a representation of concepts, relationships, and axioms that forms a foundation of reasoning about a domain"* (Janik and Kochut 2008).

As an initial step in developing such ontology this paper explores high level building-science-performance concepts in an attempt to organize them and refine them in subsequent steps into a generalized dynamic hierarchical structure. One of the most well-known generic ontologies implicitly used for reasoning and problem-solving in buildings is the *function-behaviour-structure* (FBS) ontology developed by Gero (1990). In the FBS ontology the "function" reflects the intentions of the artifact (i.e. "what the object is for"); "behavior" is causally derived from structure by physical laws under external stimuli (i.e. the environment) and represents the expected or required behavior of the artifact (i.e. "what the object does"); and "structure" represents the artifact itself (i.e. what the object consists of") to provide the intended functions to respond to the environment. The building science ontology described in this paper is built with the FBS ontology at its core.

Figure 2 describes the building science Upper Ontology, which is problem-based to acknowledge that building science problems can be of different nature, and require problem-specific knowledge, as well as problem-specific solution processes. For example, if the problem is making a basement energy efficient, the solution for a retrofit is likely different to that for a new building design. Another important aspect of the upper ontology is the association of a Performance Ontology to a Problem Ontology. This association indicates that performance is the driver for the solution of any problem; performance drives the selection of systems and components, the relevant boundary conditions, and the physical processes that are expected to impact performance; all these subject to performance constraints.

In Figure 2, the entities in the upper ontology are shown in black squares. Each of the four entities in the upper ontology is a root of its own ontology hierarchy. These entities are hierarchically refined into more specific entities to enable abstraction, i.e. to enable users to see the forest and the trees. For illustration, Figure 2 shows a refinement of two upper level entities into lower level ones described in gray squares. The fact that the ontology is problem based does not mean that the user needs a specific problem at hand to use the ontology. For example, if the user is interested in looking for some materials that can be used as part of the air barrier system of an envelope wall, then the user will simply need to search for materials, and the ontology will help, based on user input, to build an instance graph that describes materials that meet the search criteria, along with performance metrics, and associations to successful and failed uses of the material under some given boundary conditions.

As illustrated in Figure 2, the ontology is represented as hierarchical graph to enable abstraction. The ontology is intended to be used to guide building science problem solving in an integrated manner. The knowledge represented in the ontology will be used to construct instance graphs representing results from queries to the knowledge-base. Figure 2 shows, with white squares, a simple and incomplete example of instance graph representing the building envelope. Depending on the user needs, a complete instance graph will consist of complex inter-connections between nodes instantiated from one, several, all the upper level ontologies at different levels of abstraction. For example, if the user is interested in analysing the effect of changing a material or component in certain aspect of performance of that system and other related building systems, the computer will provide these connections, including boundary conditions depending on the type of analysis at hand.

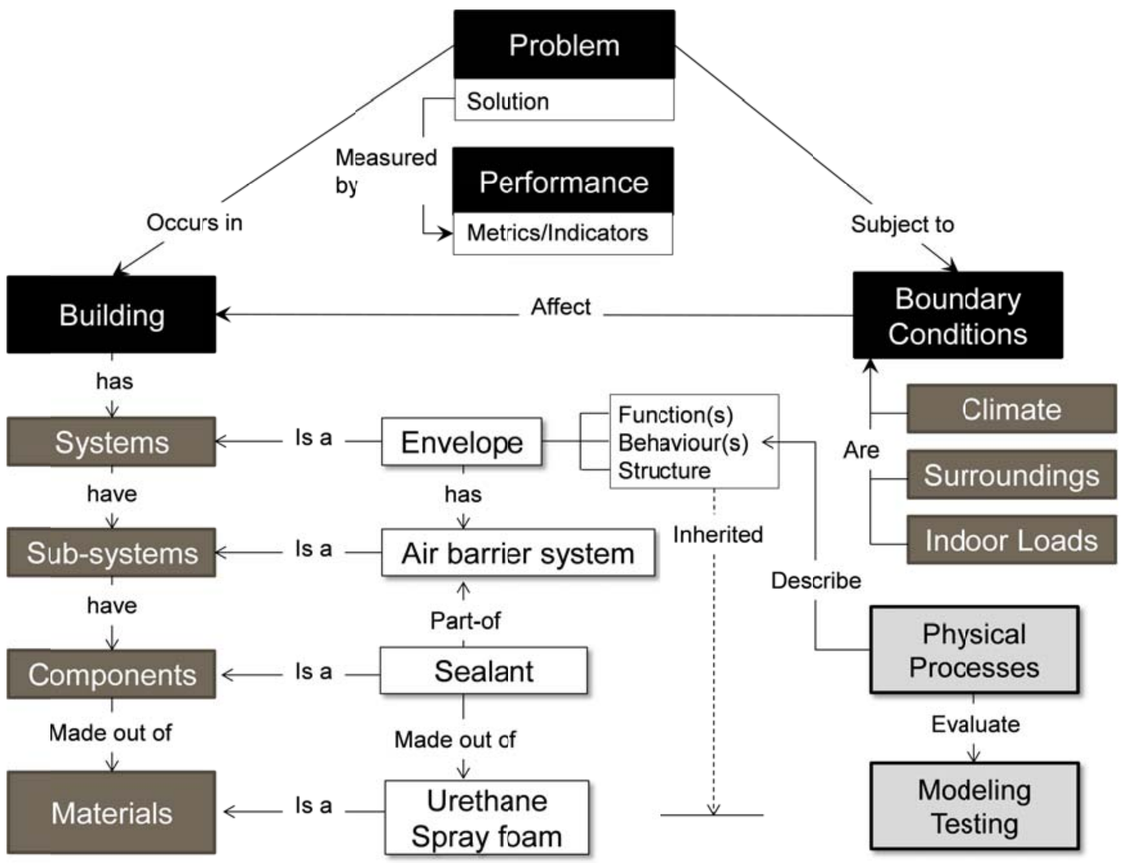


**Figure 2.** Upper level ontology

Figure 2 shows that every entity in the building has FBS properties, which are inherited from higher level abstract entities to lower level specific ones. This inheritance mechanism enables the realization of systems functions into components and materials. Finally, in Figure 2 a special entity called "Physical Processes" is at the core of any building science problem and is used to evaluate the behaviour of systems, sub-systems, components, and materials as a whole.

The proposed Upper-Ontology is built on principles of building science, and systems performance at its core, which provides a solid foundation to enable the integration of new technologies, as well as the assessment of the impact of changes on one system in other related systems at any level. For example, in analyzing an old house needing an envelope energy retrofit, the ontology may suggest upgrading the gas appliances, which may backdraft after by making the house more air tight. Or in adding more insulation to the attic of an old house, the ontology may suggest air-sealing the attic floor to minimize the increased condensation risk from making the attic colder.

Developing each sub-ontology involves knowledge acquisition, knowledge representation, prototype implementation, testing, and validation processes. For example, the knowledge acquisition process to develop the Performance Ontology is expected to build on a well-established body of knowledge from relevant individual disciplines and from efforts by LBNL (Hitchcock 2002) and NREL (Deru and Torcellini 2005) and others. Notably, Choudhary et al. (2003) proposes a mathematical model to propagate performance metrics between different levels of abstraction. The Climate Ontology is expected to help guide on selecting climate data according to the problem needs. For example, hygrothermal analysis and energy analysis need different types of climate data; similarly, wind data for cladding uplift analysis and natural ventilation analysis is expected to be different. The Materials Ontology will organize materials' knowledge according to primary and secondary functions. Note that the Materials Ontology is not intended to consist of materials databases but to include technical information on materials, such as performance metrics, testing standards, research data, case study applications, etc.

Note that the Upper Ontology and sub-ontologies are not process models acting as "strait jackets" that enforce a top-down problem-solving methodology. They should rather be seen as a "life jackets" actively responding to the users' needs: rules and entities are activated in many ways, top-down, bottom-up, or both, on demand, depending on the needs of the users.

The remainder if this paper elaborates on the "Building Science Problem" entity in the upper ontology, which is at the core to support building science integration. The paper does not describe the "Problem" ontology in detail but rather attempts to uncover patterns (knowledge acquisition) in a vocabulary to be used for its construction.

## 4. The Problem Ontology

### 4.1. Theoretical background

Table 1 groups building science problems during a building's life-cycle, along with the predominant type(s) of reasoning used to solve such problems, under the premise that supporting the solution to building science problems requires facilitating the type of reasoning involved. Just like the Upper Ontology, the problem ontology does not enforce a top-down process, but provides the rules to assist in problem-solving.

**Table 1.** Grouping of Building Science problems

| Building Life-Cycle phase | Building Science Problems | Type of reasoning |
|---|---|---|
| 1. Life-cycle planning & design | Design: integrated design, design for durability | Abduction |
| | Analysis: building physics analysis/simulation, risk analysis | Deduction |
| 2. Construction | Quality control: inspect, sample, test | Deduction |
| 3. Commissioning | Envelope & Mechanical testing | Deduction |
| 4. Service life (operation) | Failure investigation: survey, sample, test, diagnose | Abduction |
| | Monitoring | Induction |
| | Condition Assessment: survey, sample, test, monitor | Abduction → Induction |
| | Retrofit: failure investigation or condition assessment, analysis | Abduction → Induction → Deduction |

Design is abductive in nature: given a required behavior (effect) and knowledge of physical laws (rule) a structure is derived (cause). Analysis is deductive: given a structure (cause) and the application of physical laws (rule) a behavior is derived (effect). Construction and commissioning problems are deductive: a required behaviour is confirmed (effect) using standard procedures. Failure investigations are abductive: given a visible effect (behavior) and physical laws, a cause is derived. Monitoring is inductive: given a structure (cause) and a monitored behavior (effect) a generalized pattern (rule) is obtained (Raphael and Smith 2003).

Abduction requires open-world hypothesis (i.e. to produce creative alternative solutions); whereas, deduction and induction follow a closed-world hypothesis (i.e. assume that what is given is the only information to support the conclusion). In general, engineering needs to operate in open worlds, therefore abductive tasks (such as design) need to be supported by analysis (deductive) in order to encourage open-world creative solutions.

It follows that supporting abduction, design (synthesis) and diagnosis, requires a good knowledge-base to promote open-ended problem solving; while support for analysis, is based on off-the-shelf and advanced analytical tools. Maher (1990) describes three formalisms to support design/synthesis (and diagnosis): decomposition, case-based reasoning, and transformation. Decomposition uses generalizations to divide complex problems into smaller, less complex, ones. Case-based reasoning uses design experience from episodes and then compiles it and reuses it in similar problems. Transformation uses generalizations, instead of episodes, in the form of valid transformational rules, much like a language, to help derive a solution. In reality, these three formalisms are implicitly used in practice. The Ontology attempts to support the three formalisms for problem-solving.

### 4.2.Uncovering patterns

Figure 3, describes an initial organization of knowledge towards the "Problem Ontology" into five groups. In Figure 3, the intended functions of the structure (i.e. the building) are fulfilled through its behaviour subject to specific _boundary conditions_. The _level of function_ is measured through performance metrics. At the systems level, _serviceability limits_ define acceptable thresholds for building science performance. These limits, affect, in turn, the definition of the structural parameters and the indoor environmental systems. Hereafter the term **structure** is used in the broader sense of the FBS ontology to describe the building (including all of its systems).

In Figure 3, the function-performance group number 5, the _Systems_ level group, represents a systems-level integration of knowledge from groups 1 through 4. It is at this level that the individual performances of the different systems involved in the problem are evaluated and optimized together. From a knowledge-based perspective, the challenge in a systems-level integration lies on the systematic application of generic knowledge to particular problems to enable handling problem-specific and technology-specific knowledge, as well as generating new knowledge.

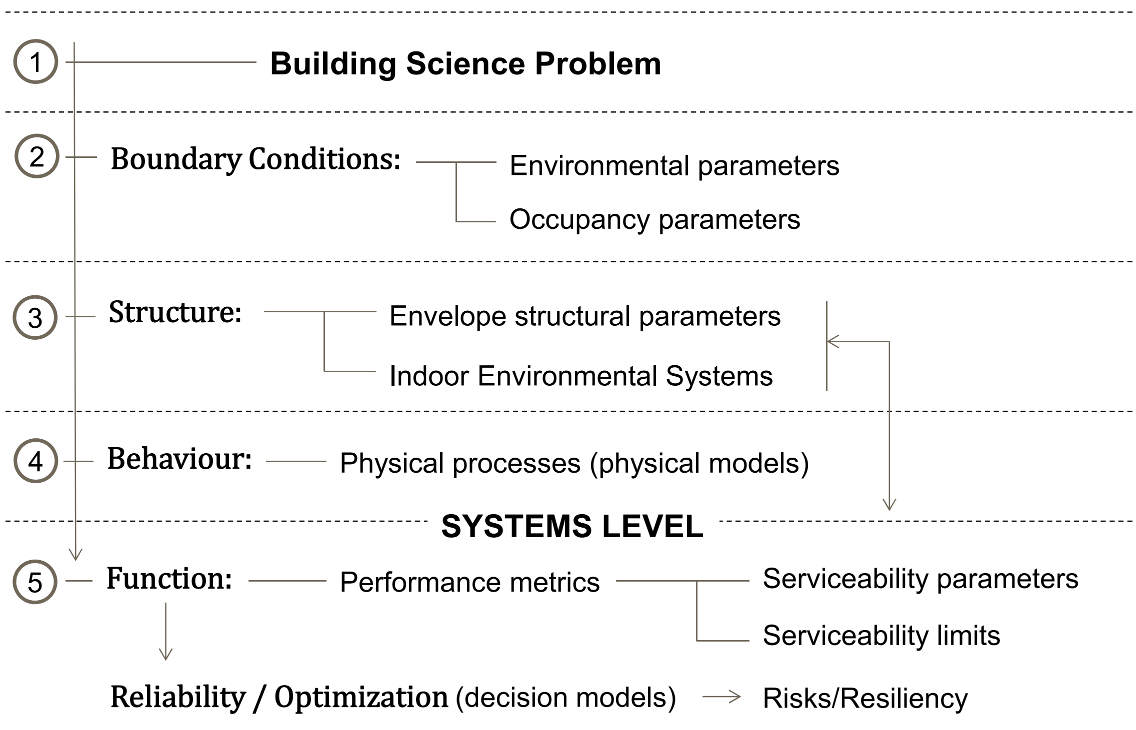


**Figure 3.** FBS ontology applied to Building Science-Performance problems

The fact that building science is concerned with serviceability performance rather than on safety performance is significant in providing knowledge support. _Serviceability performance_ attempts to determine a _level of quality_ of the structure, which unlike structural safety is not catastrophic and therefore is often not included as part of building codes.

In structural engineering, serviceability performance includes aspects such as deflection, vibration, and corrosion. In building science serviceability involves determining *acceptable limits* for parameters such as indoor air temperature and humidity, moisture content of materials, small cracks, discoloration, mold stains, fresh air exchanges, energy losses, odours, etc.; and making sure these remain controlled during service life to maintain the intended functions of a building under expected environmental and occupancy conditions. Determining a required level of quality is often based on good judgement under limited knowledge because specific scientific evidence, for example on durability and comfort, is often not available or not easily verifiable.

Knowledge support for problem-solving should be consistent with the complexity of the problem at hand, and guide on its simplification by the selection of *simplifying assumptions*. Table 2 illustrates the multi-dimensional complexity of building science problems and the possibilities for simplifying a problem to make it tractable.

**Table 2.** Complexity of Building Science problems

| Dimension | Simplifying Assumptions |
|---|---|
| Time resolution | • Hourly, daily, seasonal, typical year, service life |
| Multi-functionality Systems/Technologies | • Primary Function(s)<br>• Secondary Functions |
| Scale/Granularity | • System, assembly, element, connection, material<br>• Whole building, multi-zone, single-zone, room, personal |
| Space | • Shape, size, position, location, orientation, exposure |
| Physical processes: complexity & simplifying assumptions | • Analysis: steady-state versus transient<br>• Loads: static, dynamic<br>• Processes: single, multiple, degree of coupling<br>• Flow: 1D, 2D, 3D, laminar, turbulent, transition |
| Variant/Invariant parameters, properties | • Time invariant/variant<br>• Space invariant/variant |
| Uncertainties | • Environmental, occupancy, structural |

In building science the structure's behaviour is mainly controlled by *coupled* thermal (heat), airflow, and moisture (HAM) transport *processes*, which are driven by energy. Figure 4 illustrates the typical coupling between HAM in a hygrothermal simulation program, where "i" is the simulation time step.

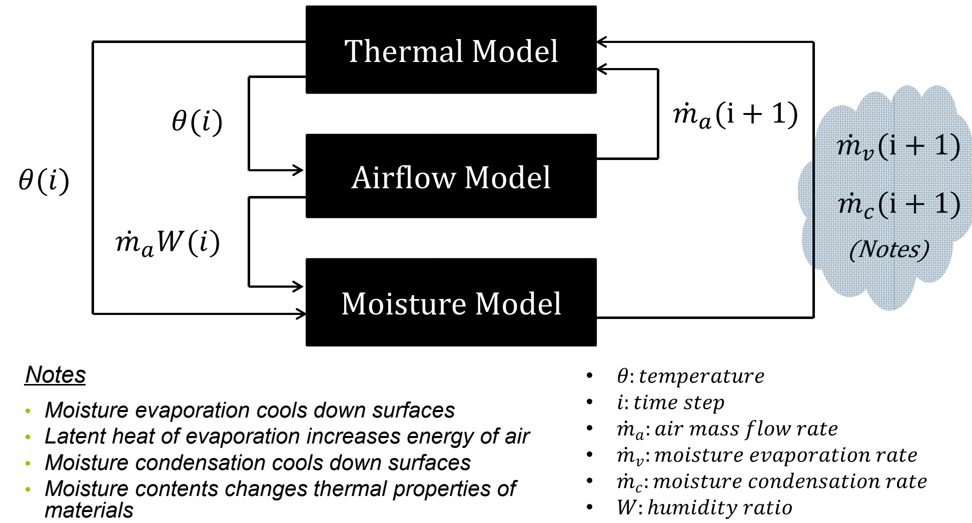


**Figure 4.** Physical processes in Building Science and examples of coupling

Section 5 presents case study that attempts to test the power of generality of the Problem Ontology. The success is measured based on how it leverages on generic knowledge to help drive problem-solving while gradually capturing problem specific knowledge.

## 5. Case Study

The case study consists of the retrofit on an unfinished residential basement to make it a living space and for energy efficiency. For the sake of simplicity, the basement retrofit focuses on the walls only. Figure 5 shows the original wall (left), retrofit alternatives number 1 (middle), and 2 (right).

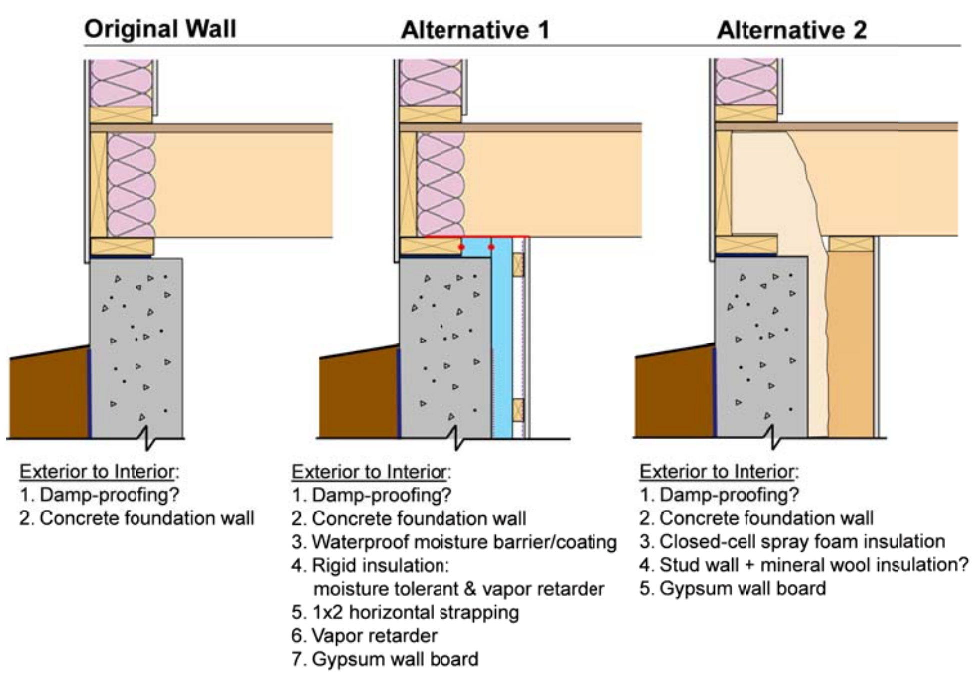


**Figure 5.** Basement wall with interior insulation and finishing retrofit

In the case study, selected vocabulary keywords are shown in italics and underlined to highlight their relevance within a problem context. For example *building age* and *condition assessment* are relevant to the *retrofit problem* which elaborates the building science problem sub-ontology. Some of these keywords are at a higher level of the vocabulary hierarchy and therefore require elaboration (e.g. *environmental loads*), and some others are at a lower level (*building age*).

### 5.1. Building Science Problem

*Retrofit*: type: energy, comfort / interior insulation, finish basement
Residential / basement / Location: Burnaby, BC / *building age*: 20 years

- *Boundary conditions:*
  *Environmental loads*: climate zone: marine / ground temperature / ground moisture
  *Occupancy loads*:
  Before retrofit: unfinished basement used for storage
  After retrofit: family room, laundry, studio
- *Structure:*
  *Envelope*: below/above grade / wall / floor slab
- *Behavior:*
  HAM/energy processes
- *Function (SYSTEMS LEVEL):*
  *Performance metrics*: energy, comfort, cost
  *Risks*: durability, health

The solution requires breaking the problem down into four sub-problems: *condition assessment*, selection of *retrofit alternatives*, *process modeling/testing*, and *analysis and design*.

### 5.2. Condition Assessment

From the condition assessment, the following observations/assumptions can be derived on the boundary conditions:

- *Climate zone*: ground thermal conditions are seasonally fluctuating but stable in summer and winter (temperature above freezing but below indoor temperature). This can be confirmed with a profile of ground temperatures at various depths.
- The ground is typically wet. Some degree of moisture flow is expected between the basement and the ground through the wall. Although no visible signs of moisture are observed.
- *Indoor moisture production:* typical.
- *Heating system*: electric baseboard.
- *Ventilation system*: no designed ventilation system. Stack-effect and wind driven air through envelope cracks and passive air inlets.

A non-invasive condition assessment leads to the following observations in the conditions of the existing structure/wall:

- Concrete is airtight (i.e. acts as an air barrier).
- The integrity of concrete is good. Minor cracks can be sealed.
- Ground water management seem to be appropriate consistent with the age of the house. However, the integrity of the damp-proofing membrane cannot be verified.
- The basement wall is expected to be wet to some degree, but with no presence of bulk moisture.

### 5.3.Selection of retrofit alternatives

Table 3 describes four retrofit alternatives. In Table 3, alternatives 1 and 2 are considered good solutions by building science experts, while alternatives 3 and 4 are often used by contractors and home renovators but not recommended from building science principles.

**Table 3.** Breaking down the retrofit problem

| Structure Condition Assessment | Structure Retrofit Alternatives (L#: Layer) |
|---|---|
| • **Description**:<br>  • unfinished basement<br>  • concrete foundation wall<br>• **Non-invasive assessment:**<br>  • Water management: ok<br>    • Land grading / drainage / gutters-downspouts / type of soil / capillarity break / …<br>  • Structural integrity: ok<br>    • Interior: minute cracks, no visible moisture<br>• **Boundary conditions**:<br>  • Climate:<br>    • Ground: type, temperature, moisture<br>  • Indoor:<br>    • Current occupancy: laundry / storage<br>    • Temperature: 21-23 degC (seasonal)<br>    • Relative humidity: 55% to 65% (seasonal)<br>• **Detailed assessment**:<br>    • Detailed structure inspection: NA<br>    • Monitoring data: NA<br>    • Field data / testing: NA<br>    • Laboratory testing: NA | **Alternative 1:**<br>• L1: Integral waterproof treatment by crystallization<br>• L2: Rigid insulation: XPS air tight, vapor retarder<br>• L3: 1x2 horizontal strapping<br>• L4: Vapor retarder: class II or class III<br>• L5: Gypsum drywall + paint (option vapor retarder)<br>**Alternative 2:**<br>• L1: Closed-cell spray-foam insulation: air & moisture barrier<br>• L2: Stud wall + mineral wool insulation (if required)<br>• L3: Gypsum drywall plus paint<br>**Alternative 3:**<br>• L1: Polyethylene vapor barrier against walls<br>• L2: 3x1 furring strips<br>• L2: Rigid foam insulation between furring strips<br>• L3: Drywall attached to strips<br>**Alternative 4:**<br>• L1: 3x1 furring strips<br>• L2: Rigid foam insulation between furring strips<br>• L3: Polyethylene vapor barrier<br>• L4: Drywall attached to strips |

### 5.4. Process Modeling

Figure 6 is an abstraction of the problem showing its boundary conditions and the coupling of the retrofit wall system with the ventilation and the heating system through the indoor environment. The problem is simplified by the fact that the only driver for moist airflow through the basement and the house is the stack effect, given that the wind is more uncertain, and that the house has no mechanical ventilation system. Therefore, the coupling between the retrofit wall, the ventilation system and the mechanical system is represented by the stack effect, the moisture sources and sinks in the outdoor environment, the indoor environment, and the ground, and the heat and moisture storage capacity of the wall.

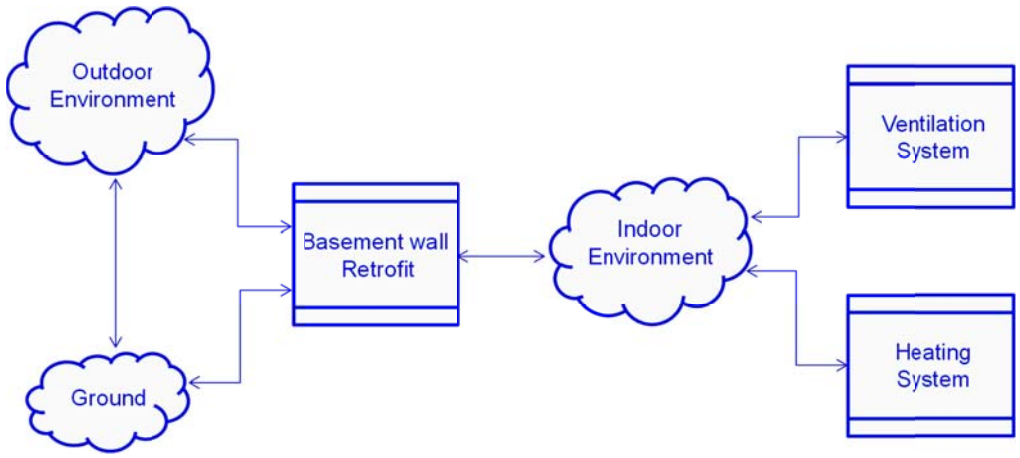


**Figure 6.** Basement retrofit problem abstraction

Figure 7 uses a modified systems dynamics stock-flow diagram (Richmond 1994) to illustrate the dynamics of the physical processes through the wall retrofit. The analysis is based on the fundamental HAM balance principles from thermodynamics which applied to this problem are the *conservation of energy* and *conservation of mass (air and moisture)*, transformed into mathematical relations and evaluated using *energy simulation* and *hygrothermal simulation* tools. The accuracy in the behaviour predictions by these tools relies on the *simplifying assumptions* by the underlying simulation models.

In the diagram, two coupled *state variables* are analyzed: the temperature and the moisture (relative humidity) at the *critical surface for condensation* (CSC), which is the coldest surface of the wall (i.e. the interior surface of the concrete). The outdoor environment, the indoor environment, and the ground are *sources* and/or *sinks* for energy and mass exchanges with the wall. The exchanges take places as *flow paths* described as double lines with arrows pointing to the *flow direction*. Valves encapsulate the properties of *transport media* to regulate the flows depending on the *transport mechanisms* and the *driving forces*.

Figure 7 also describes how the exterior environment and the ground interact with the retrofit assembly at the CSC. In all cases except for one, the existing concrete wall acts as a heat and moisture regulator (valve) and capacitor (storage). Considering moisture, concrete has a great capacity to store moisture that moves through pores, capillaries, and micro-cracks. Potential air infiltration flow bypasses the concrete wall through a basement window or the wall-ceiling interface and can reach the CSC directly.

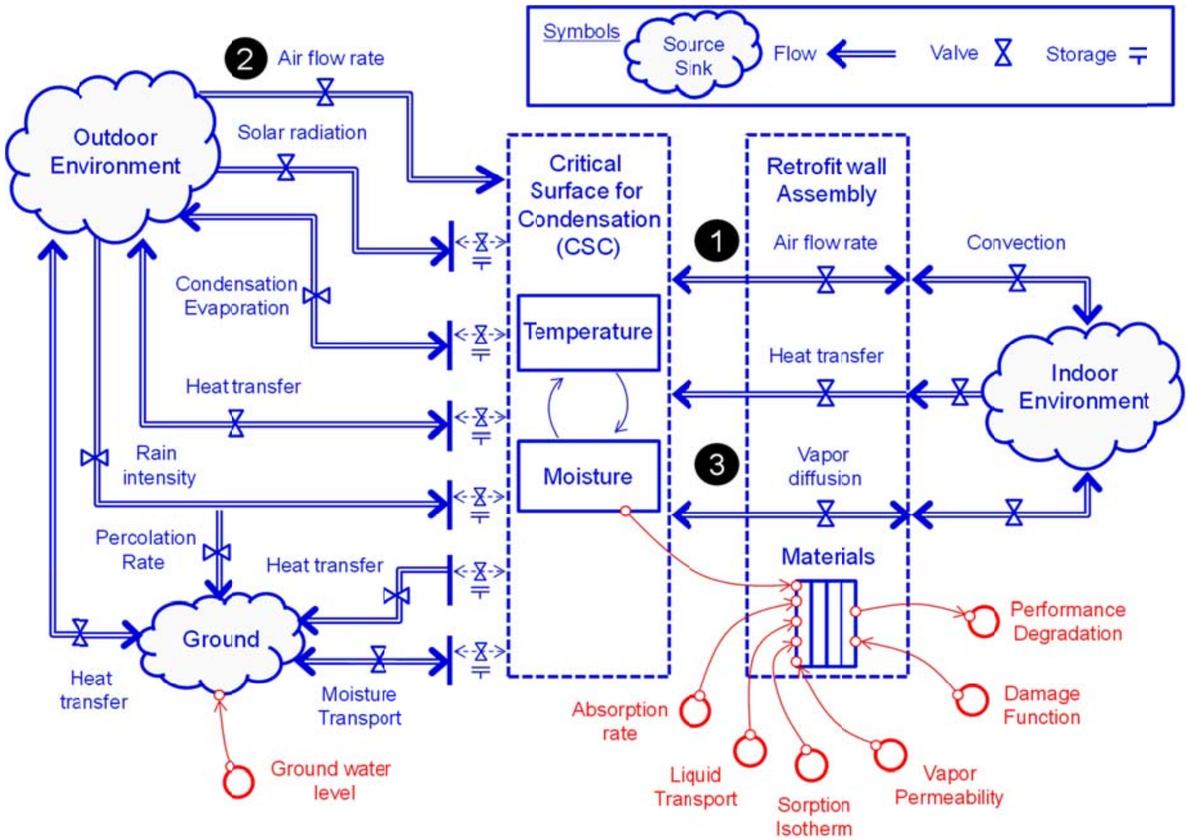


**Figure 7.** Physical processes through the retrofitted basement wall

The retrofit assembly affects the existing wall in several ways. Before the retrofit, heat and moisture (vapor) transfer take place directly between the indoor environment and the concrete wall at the CSC. After the retrofit, these processes take place through the retrofit assembly. The implications are that the concrete wall becomes colder and a CSC prone to condensation results.

The *moisture balance principle* states that in order to preserve the integrity of the wall retrofit, *wetting* needs to be controlled (it is assumed that it cannot be completely eliminated), while *drying* needs to be enhanced. To maintain this principle, flows (processes) 1 and 2 need to be completely eliminated, while process 3 needs to be controlled. Flow 1 in particular has the potential to bring warm and humid indoor air in contact with the CSC, which is now colder and more prone to condensation. Flow 2 poses risk in the summer when the outdoor air is warmer and more humid than the indoor air. Control of Flow 3 can be achieved through the proper use of a vapor retarder acting as a control/relief valve.

## 5.5. Analysis and Design

### *5.5.1. Hygrothermal Analysis*

The hygrothernal analysis based on the moisture balance principle considers the transient wetting, drying, and storage effects in the wall. As a first approximation, a steady-state vapor diffusion analysis was conducted on all the alternatives using the boundary conditions and condensation results in Table 4.

**Table 4.** Steady-state boundary conditions

| Steady State Boundary Conditions | Winter | | | Summer | | |
|---|---|---|---|---|---|---|
| | T (°C) | RH (%) | Vapor Pressure (Pa) | T (°C) | RH (%) | Vapor Pressure (Pa) |
| Basement | 20 | 45 | 1047 | 22 | 65 | 1710 |
| Outdoor | 0 | 88 | 535 | 18 | 88 | 1807 |
| Ground | 8 | 100 | 1067 | 14 | 100 | 1590 |

Given that there is no mechanical ventilation system in place, the stack effect is the main driving force controlling the air flow in the house. As a result, the basement is expected to be colder and drier in the winter owing to the cold air coming through the basement cracks and rising up through the house. In the summer the stack effect is not likely to change its direction, due to the mild west-coast summers, but its strength will be reduced significantly due to the close indoor and outdoor temperatures, which results in a warmer and more humid basement. Table 5 summarizes the results from the steady-state vapor diffusion analysis. In Table 5, the triangles pointing up indicate that no condensation is expected at the CSC, triangles pointing down mean that there is some condensation risk at the CSC, and double-triangles pointing down indicate that condensation is likely to take place.

**Table 5.** Results from Steady-State vapor diffusion analysis

| Interior | Season | Vapor Diffusion direction | Alternative | | | | Exterior | Notes |
|---|---|---|---|---|---|---|---|---|
| | | | 1 | 2 | 3 | 4 | | |
| Basement | Winter | ⟶ | ▼ | ▼ | ▼▼ | ▲ | Outdoor | Large vapour differential |
| | | ⟵ | ▲ | ▲ | ▲ | ▲ | Ground | Small vapour differential |
| | Summer | ⟵ | ▲ | ▲ | ▲ | ▲ | Outdoor | Small vapor differential |
| | | ⟶ | ▼ | ▼ | ▼▼ | ▼ | Ground | Small vapor differential |

From the analysis, the vapor diffusion is expected to change direction seasonally. However, most wetting occurs due to outwards vapor diffusion from the basement to the outdoor in the winter, due to the low outdoor temperature, and to the ground in the summer, due to the high indoor vapor pressure combined with the lower ground temperature. In Table 5, the only alternative that fails is alternative 3, with the polyethylene (PE) directly on the concrete, i.e. the CSC, because it lets the indoor moisture get right into the CSC, just to stop it there with the PE.

In all other alternatives, it seems that the concrete is coupled with the ground, acting both as a moisture sink (i.e. alternative 3 breaks this coupling). Even when there is a risk for condensation (one triangle pointing down) the moisture is expected to dry as the boundary conditions change. Obviously, if the indoor humidity increases then the condensation risk is going to be higher, for all the alternatives.

Hygrothermal heat and moisture transient analysis was also conducted using WUFI (Fraunhofer 2012), which considers not just vapor diffusion but also hygroscopic and capillary liquid flow. In general, the transient analysis confirmed the steady-state vapor diffusion results, demonstrating also the sink effect of concrete and the ground. Figure 8 shows the results from WUFI simulation on Alternative 3 indicating water accumulation at the PE vapor barrier.

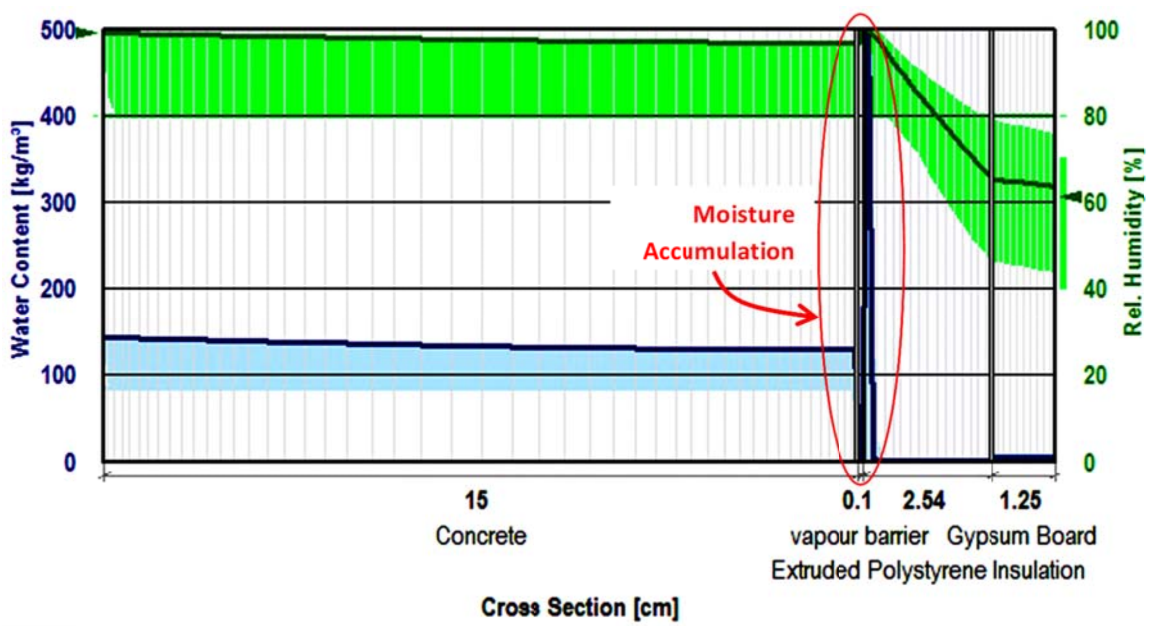


**Figure 8.** WUFI Transient hygrothermal simulation on alternative 3

Finally, a simple calculation can easily demonstrate that the amount of moisture that can be carried by indoor air intrusion into the CSC (process 1 in Figure 7) is far greater than that by vapor diffusion alone. Therefore, attention should be given to the proper air sealing of the retrofit wall. As a conclusion from the analysis, it is expected that the balance between cyclic wetting and drying will be maintained for all the alternatives, except for alternative 3.

*4.5.2. Design Principles*

Excessive moisture accumulation, i.e. breaking the wet-dry balance, will inevitably lead to the following effects at the components adjacent to the CSC:

- Deterioration of *moisture sensitive materials*:
  - *Durability indicator* → *Serviceability limit for wood* → wood moisture content limit MC > 19% (time dependent: *cumulative durability indicator*)
  - Wood: mold / decay
  - Concrete: not moisture sensitive but excessive moisture causes rebar corrosion

- Health:
    - Moisture laden microorganisms in the air
    - Respiratory problems
    - *Indoor air quality* solution: *source control*

The main design strategy to minimize the risk of moisture damage is based on providing *redundancy* that triggers one line of defense when others fail. Redundancy helps in turn build *resiliency* into the wall so that it can recover from sporadic excessive moisture accumulation events.

The *design principles* to materialize function-performance are the following:

- *Continuity of envelope functions*:
    - Energy (Thermal). Continuous thermal control function using continuous insulation with no thermal bridges for energy efficiency.
    - Air. Continuous air control function through an air-tight construction to prevent indoor moist-air migration into the wall (process 1).
    - Moisture. Continuous moisture control function that minimizes wetting and permit drying in any direction.
- *Materials properties*:
    - *Moisture capacity*. Use moisture tolerant materials, such as extruded polystyrene and pressure-treated wood.
    - *Exposure*. *Moisture sensitive materials* should be kept away from critical surface for condensation. Alternatives 1 and 2 protect the wood framing by keeping it warm and separated from the critical surface for condensation. Alternatives 3 and 4 fail to implement this principle.

Figure 9 illustrates how Alternative 1 implements the concept of *redundancy* in the retrofit with four lines of defense against moisture deterioration. As indicated in Figure 9, redundancy is built by proper application of the *moisture balance principle*, the use of *moisture tolerant materials*, and/or by avoiding the *exposure* of *moisture sensitive materials* to the *critical surface for condensation*. Figure 9 also illustrates that proper detailing is essential to the success of all lines of defense.

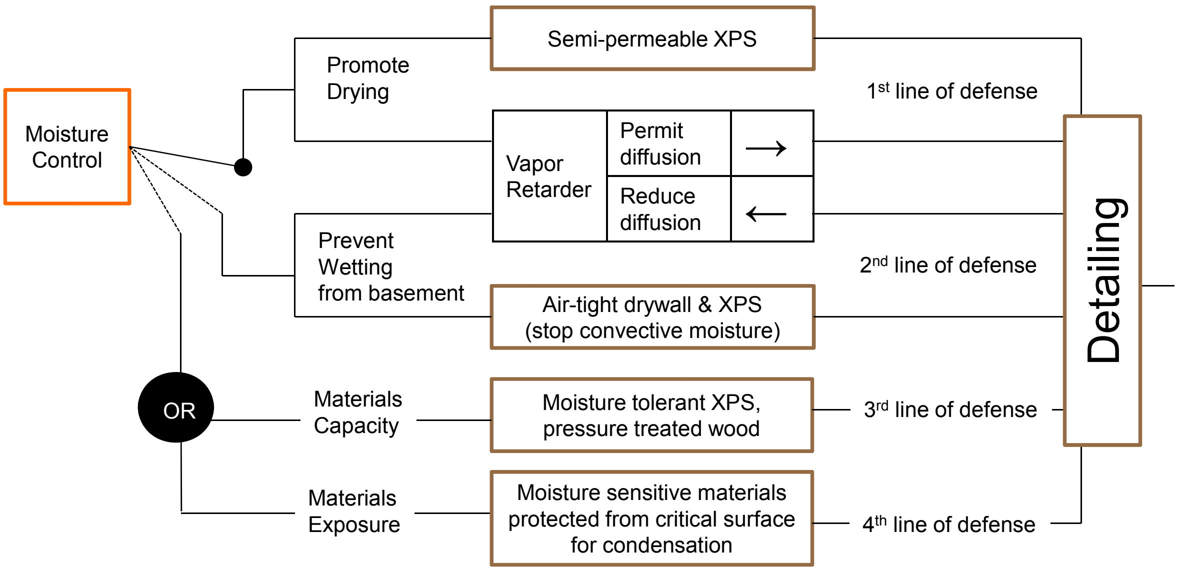


**Figure 9.** The concept of redundancy applied in Alternative 1

### *4.5.3. Detailing*

Proper *detailing* is central to building science durability. Figure 10, shows that any failure to meet the air barrier continuity requirement on the retrofit results in great damage due to uncontrolled convective moisture transport from the basement (process 1), which will likely lead to condensation at the CSC.

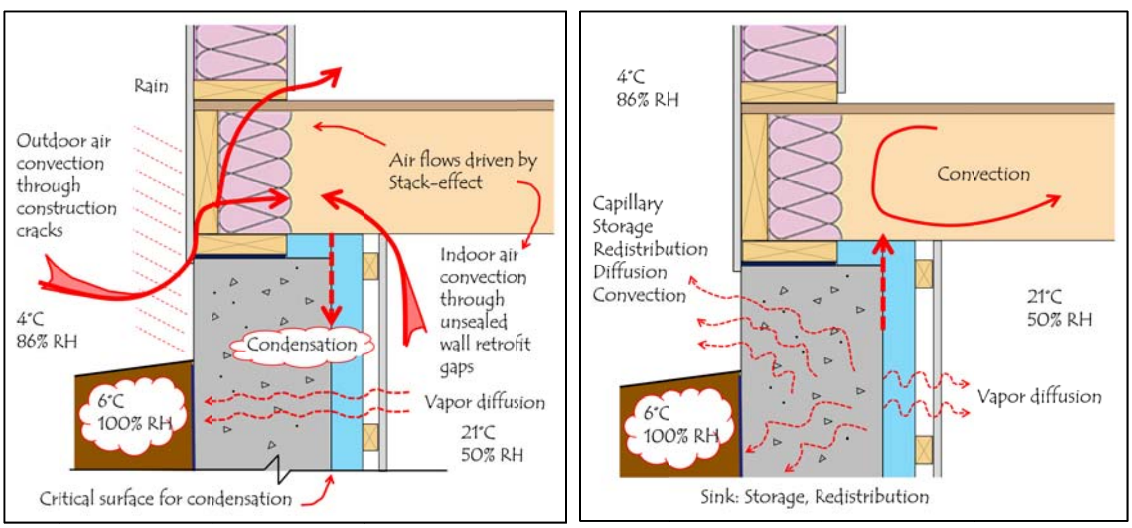


**Figure 10.** Construction detail from Figure 5: wetting (left) and drying (right)

Figure 10 also illustrates one of the limitations of the one-dimensional (1D) analyses conducted. It shows that both wetting and drying are two-dimensional (2D). Wetting may come from the top of the wall, and drying will likely occur towards the top, driven by capillarity and vapor diffusion differentials, especially in the colder periods of the year when the outdoor vapor pressure is lower.

*4.5.3. Case Study Conclusion*

A *risk analysis* would indicate that alternatives 1 and 2 are feasible, while alternatives 3 and 4 should be eliminated. From a risk/durability point of view alternative 2 seems more suitable because it eliminates the risk for air intrusion into the CSC. It is the simplest alternative because the spray foam insulation performs the thermal, vapour, and air control functions. In theory, an *optimization* model could be applied at this stage (Figure 3) to help select the alternative that optimizes performance trade-offs between comfort, energy, and cost without compromising durability. Such a model is not required for this small project.

## 6. Analysis and Discussion

Even though the case study focuses on a narrow apparently simple problem, it illustrates that at the core, problem complexity is governed by the physical processes involved and the proper use of simplifications from incomplete knowledge. Furthermore, the case study demonstrates the potential of using well-structured vocabulary to make the problem more tractable. From the case study the following conclusions can be obtained.

- Some of the patterns (i.e. keywords) in the vocabulary used in building science problem-solving are generic, such as the continuity of envelope functions, redundancy, and resiliency design principles; or the moisture balance analysis principle. Other patterns are specific, such as the critical surface for condensation.
- The solution to the problem involves abstraction and refinement. The solution process involves the combination of top-down and bottom-up knowledge. For example, bottom-up knowledge of materials properties is used in the problem to implement intended system functionalities.
- Refinement between levels of abstraction is accomplished through knowledge on the generic system functions to be materialized. Generic envelope system functions in this particular problem are the continuity of the thermal, air, and vapor control layers. Generic functions have several possible physical realizations and representations.
- Such generic knowledge can become a means for guiding the generation of new knowledge that may be required, for example, for integrating innovative technologies in buildings, which may include aspects such as constructability.
- A graphic process modeling language greatly helps appreciate and communicate the dynamics of the physical processes involved. In his paper, the systems dynamics flow-stock diagram (Richmond 1994) was used. However, several languages exist for modeling physical systems, such as Modelica (Fritzson and Engelson 1998), bond graphs (Paynter 1961), and Simulink (MathWorks 2012). All the above languages are operational, in the sense that besides being graphic, they model mathematically the behavior of physical systems.

- In building science practice risk analysis is scenario based, which is the approach used in the case study. However, risk analysis is probabilistic in nature, which involves the development of probabilistic performance functions that reflect the variability of materials and systems and their performance degradation; as well as the inherent uncertainty in the boundary conditions. Further research is required to investigate how to integrate the probabilistic dimension in building science problem solving.

**Conclusions and Further Work**

This paper has presented a knowledge-based methodology for building science-based systems performance integration. At this level of the research, the goal is to achieve generality of a vocabulary to explicitly handle all aspects of building science related problems. The high-level ontology presented in Figure 2 attempts to capture such generality. The case study presented demonstrates its applicability in a practical situation. Further work is required to elaborate on the ontological hierarchy and test it with more complex case studies to further demonstrate the applicability and usefulness of the methodology in helping address building science problems which it is argued are at the core of building performance integration. At some point, in order to enable further development of the ontology an accepted formalism for knowledge representation will need to be used and transformed into a software prototype. A platform for knowledge-based systems creation will be investigated.

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# A CRITICAL COMPARISON OF CONSTRUCTION ENGINEERING AND ARCHITECTURAL ENGINEERING CURRICULA
## 2013 Architectural Engineering Institute (AEI) Conference

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## ABSTRACT

The nation's Construction Engineering (ConE) degree programs place a large number of their graduates into the commercial/architectural construction industry. ConE programs are often collocated with Architectural Engineering (ArchE) degree programs, a closely related discipline. Allegorically, ConE and ArchE are like brother and sister, sharing a common curricular foundation. The study's objective is to explore improving the preparation of ConE graduates for the commercial industry by adding an option to minor in ArchE. This paper reports the result of a comparative content analysis of the similarities and differences in ArchE and ConE curricula and quantifies the additional coursework necessary to add an ArchE concentration. The findings are based on a curriculum survey of every ABET accredited ArchE degree program. The study's findings are validated by a case study comparative analysis of ArchE and ConE programs at the University of Nebraska and the ConE program at Iowa State University. The paper finds a significant degree of overlap in each discipline's accreditation requirements and, depending on a given programs' existing curriculum, that adding an ArchE minor to a ConE degree program can be accomplished by including an average of nine additional credits.

## KEYWORDS

Construction, Curricula, Emphasis, Minor, Relationship

## INTRODUCTION

Construction Engineering (ConE) and Architectural Engineering (ArchE) degree programs are so closely related that, in some cases, there are as few as nine credit hours of different courses separating their curricula. ArchE bachelor's degree programs vary from four year programs to five year programs (MUST 2011, PSU 2008, NU 2010). Areas of emphasis available in a university's specific ArchE program may include structural; heating, ventilation, and air conditioning; electrical; construction; lighting; fire protection; plumbing and medical gas piping; and/or acoustics. Some ConE bachelor's degree programs offer similar areas of emphasis. For example, Iowa State University (ISU) offers ConE degrees with areas of emphasis in building, heavy/highway, mechanical, and electrical (ISU 2012). ConE graduates with an emphasis in building, mechanical, and electrical typically enter the commercial/architectural construction industry. At ISU approximately 85% of ConE students are in this category. Architectural engineers and construction engineers work together in industry and they may even fill some of the same roles. Offering both ArchE and ConE degree programs within the same department/university could provide graduates with a better understanding of both sides of the building design and construction industry and service a long term need to enhance constructability knowledge among both groups (Yates and Battersby 2003).

## Background

Traditionally, the designer and the construction contractor have essentially worked apart from each other (Brown 2002). Thus, the constructor's understanding of the design process was limited, as was the designer's understanding of the process to build what was shown in the construction documents. Construction documents contained little, if any, information on how to actually build the project, placing that burden on the contractor and controlling it using construction submittals for temporary structures like formwork, falsework, and shoring (Koch et. al 2010). These extensions of the final design are completed by construction engineers, who are often required by the contract to be licensed professional engineers and their work is expected to be submitted with the engineer's seal (Yates and Battersby 2003). In 2001, the National Council of Examiners for Engineering and Surveying recognized the need to license ConEs and voted to include construction issues in its study to update Civil PE exam content. In 2007, ConE graduates were able to sit the first PE exam with a ConE module (Johnson 2006).

The quality of the final construction product is literally defined during the design process (Gransberg and Windel 2006). Thus, providing entry-level engineers of all types with an understanding of both design and construction would seem desirable. Research has shown that the quality of the construction documents is related to the designer's knowledge of the construction process. Yates and Battersby (2003) found "that architects and engineers with extensive construction experience could produce the most effective documents." However, this is difficult given the nature of most careers in the design professions where architects and engineers must spend most if not all of their early careers piling up sufficient professional design practice experience to become licensed in their fields. The next most common response was by "allowing the constructor to be involved in the design from conceptualization." (Yates and Battersby 2002).

The advent of alternative project delivery methods like design-build and construction manager-at-risk literally provide the constructor the opportunity to participate in the design process (Shane and Gransberg 2010). A recent report found that nearly 40% of non-residential commercial construction projects where delivered using alternative methods (DBIA 2011). Thus, extrapolating the statistic leads to the notion that ArchE and

ConE students will find themselves working on projects where they are expected to understand the other's profession nearly half the time.

A study done by Yates and Battersby (2002) probed the question of how much construction experience a building designer should have to produce a constructable final design. These researchers surveyed a large cross-section of design and construction professionals regarding the content of training programs for entry-level architects and engineers. The study produced results that bear on the knowledge needed by ArchE and ConE graduates to properly implement constructability at the project level. One section of the survey asked a group of questions related to construction field experience, designer construction knowledge, and design processes and had the following results:

- "66% of the respondents thought it important for designers to have construction field experience prior to starting their design careers;
- 91% thought it important for designers to learn about construction methods, construction processes, and construction management as part of their formal education;
- 76% thought designers should be required to obtain construction field experience prior to receiving professional registration;
- 79% felt that the amount of claims against a design firm's errors and omissions insurance would be reduced if designers had construction field experience." (Yates and Battersby 2002)

The above discussion leads one to infer that a university engineering degree program should include content from both design and construction regardless of the major. Determining the difficulty of achieving the required integration of design and construction education is the objective of this paper.

**Definitions**

ArchE can be a term that causes some confusion; is it Architecture or is it Engineering? The University of Nebraska Durham School defines ArchE as, "focus[ing] on the design, integration and coordination of building engineering systems, including structural systems; heating, ventilating and air conditioning systems; acoustical systems; and lighting and electrical systems" (UN 2010). ArchE can, in a rough way, be thought of as the design of the "guts" of a building. Architects design the aesthetics, general flow, etc. Architectural engineers design the systems inside/throughout the building that help make it functional and comfortable. ConE can also be a confusing term; how does it differ from construction management degrees? To again quote the University of Nebraska Durham School, ConE "integrates engineering and construction management" (UN 2010). Construction engineers are engineers. They understand engineering principles and are eligible to sit for the Professional Engineer licensing exam. Approximately 90% of ISU ConE students sit for the Fundamentals of Engineering exam while they are pursuing their undergraduate degree. Not all construction engineers work for contractors, some work for owners, manufacturers, and even design firms. The relationship between ConE and ArchE is huge. They are family, like brother and sister - very related with noteworthy similarities and also obvious differences.

**Historical Information**

ArchE has been around for over a century. According to their website, the ArchE program at Pennsylvania State University was founded in 1901 (PSU 2008). The program earned accreditation in 1936 from the Engineers' Council for Professional Development, now known as the Accreditation Board for Engineering and Technology (ABET), when they began accrediting engineering programs (ABET 2011). Kansas State University and University of Colorado also had accredited ArchE programs in 1936. By 1980 there were nine accredited ArchE programs in the United States, with more programs to come. There was a "surge" in the late 1980's with four more Architectural Engineering programs earning ABET accreditation. Over the past eleven years, an additional four ArchE programs have been awarded ABET accreditation, resulting in a total of seventeen currently accredited programs (ABET 2011).

ConE has seen similar growth over the past decade (Johnson 2006). In 1958 the ConE program at North Carolina State University was awarded accreditation. In the late 1970's and 1980's four more ConE programs were accredited. The recent "surge" in ConE programs occurred in the late 2000's with six programs earning accreditation over a three year period. There are currently twelve ABET accredited Construction Engineering programs in the United States (ABET 2011).

Illustrated in Figure 1 is a timeline for ABET accreditation of ArchE (bottom of chart) and ConE (top of chart) programs (ABET 2011).

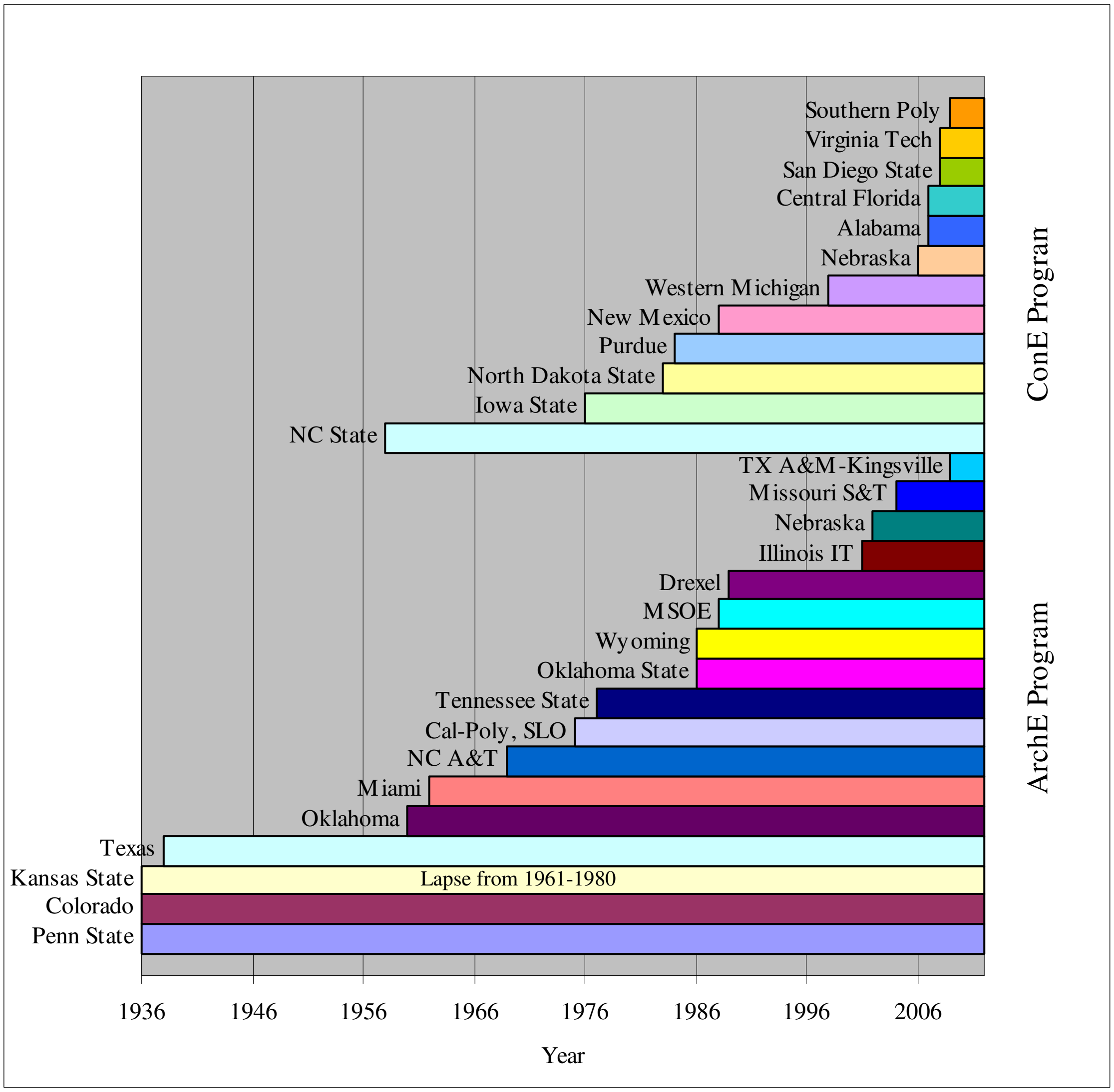


**Figure 1. Time of ABET Accredited ConE and ArchE Programs**

## Curricula

The ConE program at ISU emerged from what was originally an ArchE program that was primarily a combination of architecture and structural engineering. The ISU ConE program as it is today was founded in 1951 and earned accreditation in 1976 (ISU ConE 2010). With its roots in ArchE, the similarities between the program's curricula and that of some ArchE programs is not surprising. A comparison of the current ISU ConE-Building Emphasis curriculum with the Missouri University of Science & Technology ArchE curriculum shows an overlap of over 100 credit hours of coursework, by credit hour (MUST 2011). The curricula were compared by course title and description and number of credit hours. The overlap is illustrated in Figure 2.

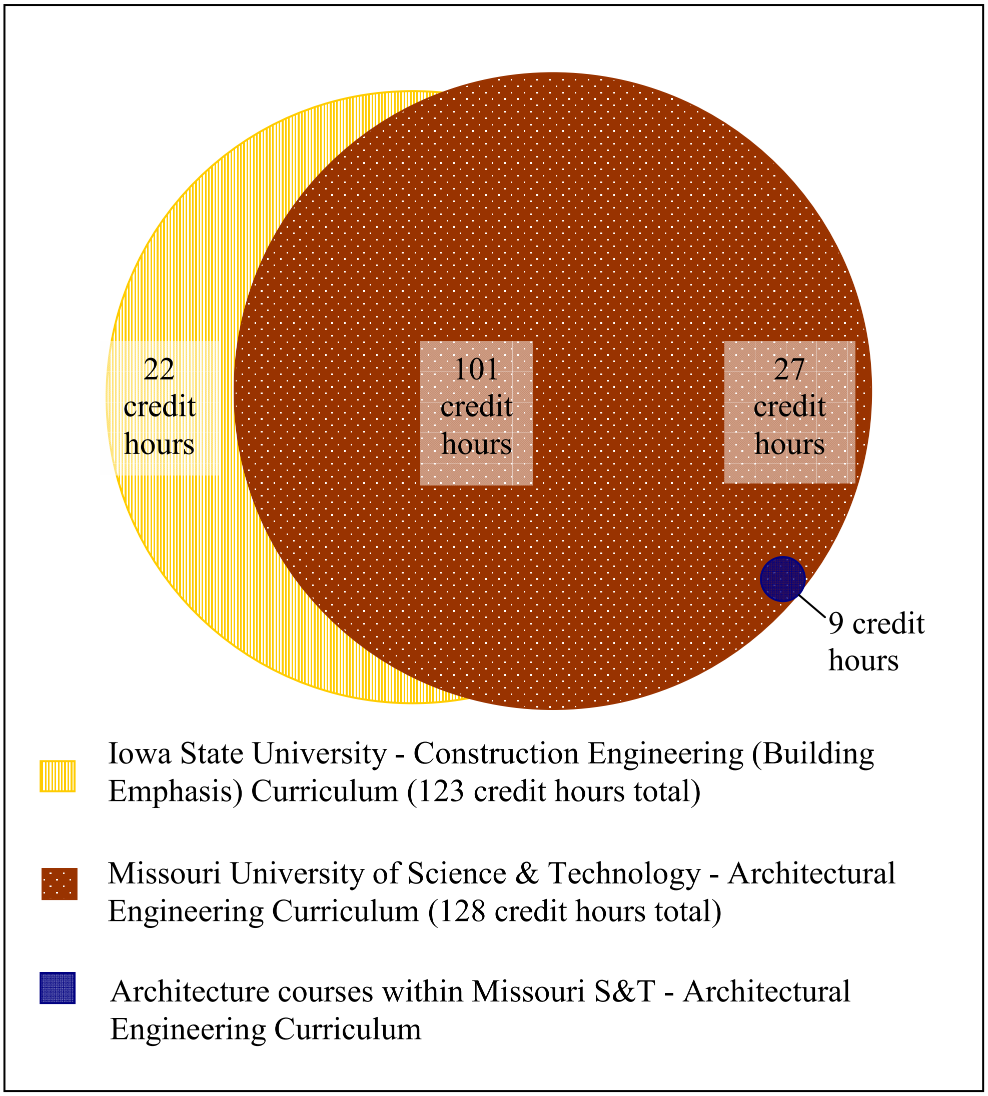


**Figure 2. Overlap of ConE and ArchE Curricula**

Of the twenty-seven credit hours from the Missouri S&T ArchE curriculum that do not overlap with the ISU ConE curriculum, all have a similar course that is currently offered at ISU. Only fifteen of those credit hours do not currently have ConE students (building-, mechanical-, and/or electrical-emphasis) taking them. Within the non-overlapping eighteen credits that ConE students are not currently taking there are nine credit hours of architecture courses. ISU has a top rated architecture program that offers similar courses to those that Missouri S&T ArchE students are required to take (MUST 2011). Currently, ConE students are not required to take architecture courses, but with the courses being offered on campus, there is potential for ISU to offer a ConE degree with an ArchE minor, ArchE emphasis, ArchE graduate degree, or even an ArchE bachelor's degree.

In further comparison, course offerings at ISU, not just those within the ConE curricula, overlap greatly with courses in ArchE curricula at various universities. Figure 3 shows the number of credit hours for five different ArchE programs: Missouri University of

Science & Technology, University of Colorado, University of Nebraska, Pennsylvania State University, and Kansas State University. The credit hours are shown in four different "bins," categorizing them as:

1. having a similar course currently offered at ISU within the Civil, Construction, and Environmental Engineering (CCEE) Department;
2. having a similar course currently offered at ISU, outside the of the CCEE Department, with ConE students currently taking the course;
3. having a similar course currently offered at ISU, outside of the CCEE Department, but without ConE students currently taking the course; and
4. not currently having a similar course offered at ISU.

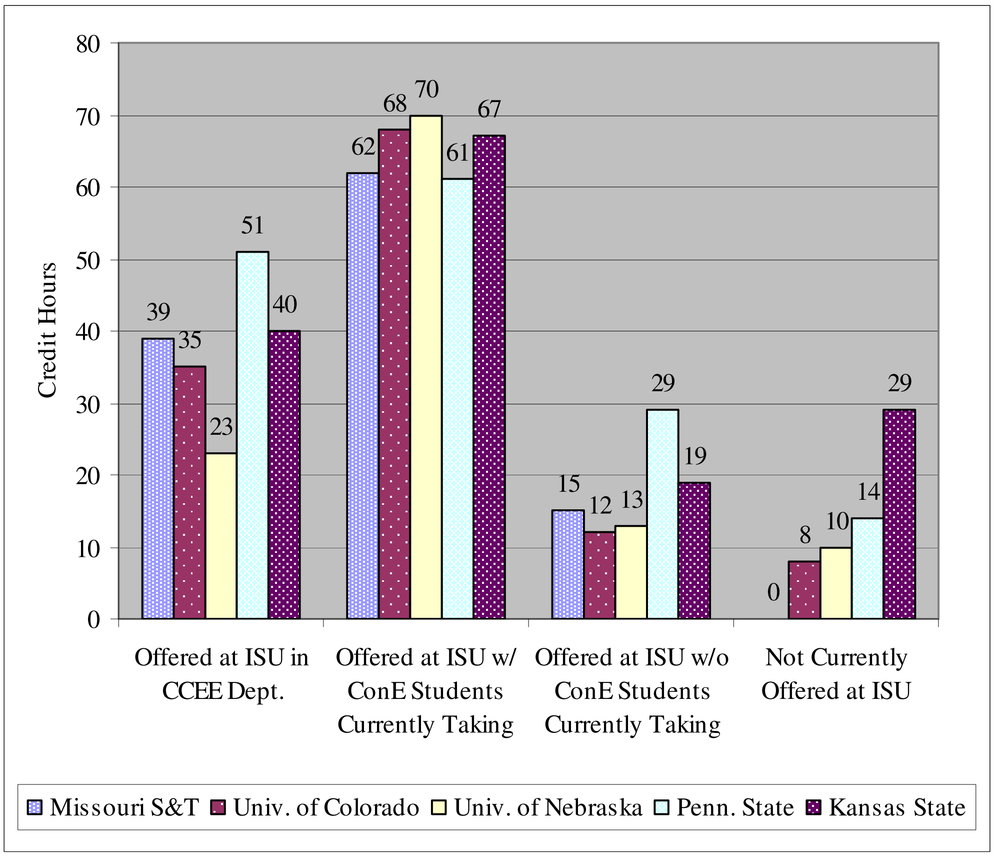


**Figure 3. Comparison of ArchE Curricula with Current Course Offering at ISU**

Among the courses that are offered at ISU without ConE students currently taking them, there are a number of Architecture courses. These courses can be grouped, by credit hour, into three categories:

1. Architectural Design and/or Analysis,
2. Architecture-related History, and
3. Introduction to Architectural Engineering (or ArchE Orientation).

Having Architecture, ArchE, and ConE students working together during their undergraduate education would provide cross-industry understanding and experience (Yates and Battersby 2003).

## CONCLUSION

As shown in the previous chart, ISU currently offers courses that are similar to 140 credit hours of courses in the Pennsylvania State University ArchE curricula. While the authors are not advocating that all 140 hours be taken by a hypothetical ISU ArchE student, the number represents sufficient course credits to populate a bachelor's degree without the need to develop any new courses or hire new faculty at ISU.

In conclusion, ConE programs could potentially add an ArchE specialization, minor, graduate program or even separate degree program without the need to increase faculty or develop new courses. Table 1 identifies proposed course types with number of credit hours that could be required for three potential ArchE options within the ISU ConE program.

**Table 1. Proposed ArchE Options for ISU ConE Program**

| ArchE Minor | | ArchE Emphasis | | | | MSCE with ArchE Option | |
|---|---|---|---|---|---|---|---|
| Cr. Hrs. | Course Type | Cr. Hrs. | Course Type | Replacing this Course in Current ConE-Building Emphasis Curriculum | | Cr. Hrs. | Course Type |
| 6 | Arch. Design | 3 | Arch. Design | 3 | ConE 340-Conc. & Steel Constr. | 12 | Required ConE Courses |
| 3 | Arch. Analysis | 3 | Arch. Analysis | 3 | ConE 322-Const. Equip. | 6 | Directed Electives |
| 3 | Arch. History | 3 | Arch. History | 3 | SSH Elective | 3 | ConE Elective |
| 3 | Dynamics | | | | | 3 | Arch. Design |
| | | | | | | 3 | Arch. Analysis |
| | | | | | | 3 | Arch. History |
| 15 | Extra | 9 | Total (New) | 9 | Replaced=0 Extra | 30 | Extra |

For a separate ArchE bachelor's degree, a ConE program similar to that at ISU could add three to ten credit hours of architectural design/analysis, three to six credit hours of architectural history, and an introduction to ArchE course and be comparable to the ArchE curricula at Missouri S&T. Adding a building acoustics course, one engineering dynamics course, two additional credit hours of lighting, and one more credit hour of electrical would put the ISU ConE curriculum on similar track as many currently ABET accredited ArchE programs. On the flip side, ArchE programs could also add a ConE option with few revisions.

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# ARCHITECT AND ENGINEER COLLABORATION: THE SOLAR DECATHLON AS A PEDAGOGICAL OPPORTUNITY

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## ABSTRACT

While close collaboration between architects and engineers in building design is a well-recognized necessity, we still educate students in each of these professions separately (and generally in isolation). This paper describes the experience of integrating teams of architecture and engineering students as they progress through the design and construction of a home for the 2013 Solar Decathlon competition. This competition requires that engineering and architecture students, in addition to other disciplines, design, build, and operate a net-zero energy solar house prototype.

The Solar Decathlon experience has identified three critical aspects for interdisciplinary collaboration: project logistics, the design process, and the collective values of the design team. Among the three, the design process is the aspect that seems to offer the greatest opportunity for innovation, especially as it relates to information technologies and building information modeling (BIM). BIM, required as a Solar Decathlon deliverable by the U.S. Department of Energy, provides an excellent conceptual framework for organizing teamwork and interdisciplinary collaboration.

This paper describes how a BIM management system was used by students as a design tool and how it was used to support a collaborative interdisciplinary team approach. Also described are how the students' design processes were impacted by the use of BIM and how this facilitated an early collaboration with engineers. Our experience shows that the collaborative design process and the effectiveness of the teamwork still depend on conventional design review methods, such as face-to-face interactions, which enable the students to understand and appreciate different professional philosophies and values. Such coordination is greatly augmented by a BIM methodology, which allows the productive participation of different disciplines while ensuring that the responsible team members maintain control of the design in their area of expertise.

**Keywords**: architectural education, BIM, engineering education, Solar Decathlon

# 1. INTRODUCTION

The 2013 Solar Decathlon is the sixth iteration of an international competition that challenges educational institutions to design, construct, and operate a net-zero-energy house under conditions that engender high expectations for performance and intense public scrutiny. The competition involves ten distinct contests—several of which are primarily engineering-based and some of which are primarily architectural. Successful teams must realistically involve multiple disciplines and these disciplines must work closely together. The Solar Decathlon requires that teams submit key deliverables in Revit, an implementation of BIM (building information modeling) software. Team Kentuckiana, one of 20 entries for the 2013 Solar Decathlon, involves engineering students located at the University of Louisville, architecture students from Ball State University (Muncie, IN), and assistance from faculty at the University of Kentucky (Lexington). Collaborative design across a distance is critical to success—it is also of substantial interest as pedagogy for architectural and engineering education.

# 2. THE SOLAR DECATHLON AND INTEGRATED DESIGN

## 2.1 Integrated design in practice and pedagogy

Collaboration has long been a prerequisite for successful building projects of any reasonable scale. Such collaboration has involved a range of parties (disciplines), including architects, clients, engineers, landscape architects, code officials, and others. The interrelationship between architects and engineers is particularly important to project success when the project is complex or seeks high-performance outcomes. Historically this architect-engineer relationship has tended to be sequential; so much so that it has often been described as a relay, with information handed from the architect to the engineer in a just-in-time manner. The growing demand for high-performance buildings seems to suggest that what was formerly considered a "just-in-time" collaboration is now more likely to be seen as a "too-late-to-do-much-good" arrangement.

Revised modes of architect-engineer interaction have been described under a variety of terms. "Integrated design" appears to have gained traction as a term with professional recognition. Two key professional organizations have slightly different takes on the specific terminology related to this collaboration and its essential characteristics.
The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) uses the term "integrated building design" (IBD), which it defines as "a collaborative process of preparing design and construction documents that result in optimized project system solutions. For IBD to succeed and be beneficial to the project, the entire project delivery team must be committed to understand, and remain engaged and involved in the process from project inception through operation and maintenance. An integrated design process discourages sequential philosophy and promotes holistic collaboration of the project team members during all phases of project delivery. Emphasis is placed on optimizing system solutions that are responsive to the objectives defined for the project. Optimizing system solutions requires the participation of all team members." (Baumann, 2009)

The American Institute of Architects (AIA) uses the term "integrated project delivery" (IPD), which it defines as "a project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction. IPD leverages early contributions of knowledge and expertise through utilization of new technologies, allowing all team members to better realize their highest potentials while expanding the value they provide throughout the project lifecycle." (American Institute of Architects, 2007)

The virtues of a more interactive collaborative approach to building design, regardless of the specific terminology employed, are being touted to the design professions (Elvin, 2007). ASHRAE devoted its 2008 annual international webcast to *Integrated Building Design: Bringing the Pieces Together to Unleash the Power of Teamwork*. Architect-engineer collaboration through an integrated design process is being pushed to practicing design professionals. Is this approach, however, being introduced to architectural and engineering students? The answer to the above question is: it depends. It depends upon whether one looks at architectural education or engineering education; it also depends upon how deeply one looks. ABET (previously The Accreditation Board for Engineering and Technology) requires that engineering graduates have "an ability to function on multidisciplinary teams." (ABET, 2011) This could be interpreted as an expectation that engineering students in building-related disciplines be able to work with architecture students. Real-time, give-and-take collaboration between architects and engineers is not, however, the only possible reading for this criterion. In architectural education, there are currently no requirements for collaboration (i.e. integrated design experience). The National Architectural Accrediting Board includes in the list of requirements for graduating architecture students "Collaboration: *Ability* to work in collaboration with others and in multidisciplinary teams to successfully complete design projects." (NAAB, 2009)

In academia, however, it is often exceptionally difficult to engage students in projects that truly provide or demand interdisciplinary collaboration as envisioned by the integrated design process. Appropriate counterpart disciplines may not be available on or near campus. Competing accreditation demands may make collaboration difficult. Promotion and tenure systems may discourage innovative academic explorations. Schedules may not mesh between departments or institutions. Enter the Solar Decathlon competition.

**2.2 The Solar Decathlon**

The Solar Decathlon is a biannual competition for solar-powered houses sponsored by the U.S. Department of Energy and open to teams of university students. Each team is required to design, build and operate a net-zero energy house with a floor area of between 600 and 1000 $ft^2$ (56 and 93 $m^2$), and a target cost of less than \$250,000. The twenty teams selected to compete for the 2013 Solar Decathlon are required to submit a number of design deliverables before assembling the house on the competition grounds in Orange County Park, California. Team Kentuckiana is one of these teams and is a partnership of three universities: the University of Louisville, KY; Ball State University, IN; and the University of Kentucky. The team includes mainly students of engineering and architecture, but also a number of students from other programs (such as construction management, business, communication, interior design and landscape architecture).

### 2.3 BIM in education

One of the main design deliverables during the course of the competition is a BIM model created in Autodesk Revit, an application which is widely employed in architectural and engineering practice but, in our experience, is not yet common in academic environments. There are three components of this authoring tool: Revit Architecture, Revit MEP (Mechanical Electrical Plumbing) and Revit Structures (integrated as one package in the 2013 version). The model generated in each discipline can be linked to cross disciplines for coordination of the respective design elements. With the models linked together during the design process, checks can be run to analyze conflicts or clashes between the components as well as facilitate optimization of the building design and system performance. When the design is completed the models are often handed off to contractors to use as a primary reference for construction. At Ball State University, collaborative use of this modeling is taking place—with construction management students, who can take off quantities directly from the three-dimensional model, and with interior design students, who can work on furniture, lighting, and other interior components within this virtual three-dimensional space.

What place has BIM in architectural and engineering education? Is this an effective method to prepare students for new models of integrated practice? As mentioned earlier, BIM does not have yet a significant impact on how educators teach architecture (Smith, 2012). Other educators predict that "with the increased attention on BIM software and its increased availability to students, we are likely to see BIM permeate (if not dominate) the studios within the next few years. However, careful attention must be paid to the impact of this particular tool on the curriculum. We must ask: what role should BIM have in architectural education and where is its appropriate place in the curriculum?" (Cheng, 2006) The architectural pitfall looming in such questions is to see BIM only as a form of three-dimensional modeling, missing its fundamental nature as an interdisciplinary collaborative tool—able to accept, process, share, and integrate information.

## 3. THE TEAM KENTUCKIANA DESIGN PROCESS

### 3.1 Process phases

The Team Kentuckiana design process, leading to Design Development deliverables, went through three phases involving different forms of interaction and three-dimensional modeling. The first was a conceptual phase when design strategies and problem solutions were developed through an ongoing discussion between architecture and engineering students. A large number of potential solutions were presented by architecture students during the course of the fall semester of 2011, and critiqued by engineering students. Three-dimensional modeling using a variety of architectural modeling software was used as a means of improving communication and, though not used as a tool for direct collaboration, allowed the capture of engineering input early in the preliminary design process where this input can have the greatest effect on the performance of the end design.

The conceptual design phase was followed, during the spring semester of 2012, by the schematic design phase. Because a Revit model was required as a competition deliverable, all architecture students were basically required to use this software. Revit is not taught in architectural courses; therefore training sessions were set up during the semester. The architecture student team was organized into three task groups: Envelope, Interior, and Exteriors. A common Revit model was created and uploaded as the central file on an external server, also accessible to the engineering students. Two graduate students, one in engineering and one in architecture, were appointed Project Manager and Architecture Project Manager (respectively) with the charge of managing the Revit collaboration.

The architecture students were able to integrate the engineering input during joint design sessions (Figure 1), so there was no need for design review tools during the schematics phase. Each task group had design responsibility in their area and had to coordinate or negotiate changes that affected another task group's decision. For instance, changes in the envelope dimensions affected all task groups, while changes in the interior floor plan were coordinated only through the Interiors group.

Fig. 1 Architecture and engineering students collaborating in the same studio space at Ball State University (ARCH 402, spring 2012, Professor Michele Chiuini).

In the third phase, as students moved toward a final design for the Design Development submission, all team members continued to use Revit Architecture 2012. Intermediate experimentations, however, were made using other three-dimensional modeling applications (such as Rhinoceros and Sketchup).

### 3.2 BIM coordination

The Revit-model management system raised the issue of ownership of design decisions, creating occasional tension between task groups. Difficulty in solving conflicts was mainly due to lack of effective communication when work was done in remote locations, outside the studio. Similar to what happens in a professional office, sharing files on a common server still requires physical proximity to alert collaborators of problems and errors. Thus, it was decided that 1) all Revit work should be done in studio when most of the team members were present, and 2) the central file should reside on an internal university server, to be shared with the engineering team only for design reviews. This decision was paralleled by the engineering student team, which was working on the Revit MEP and Revit Structures versions of the central file created in Revit Architecture (Figure 2).

The design process between schematics and design development was particularly indicative of the problems of BIM-based interdisciplinary collaboration. The schematic design solution was submitted relatively early when the design was emerging from the conceptual phase and was not completely defined architecturally. At that stage the design

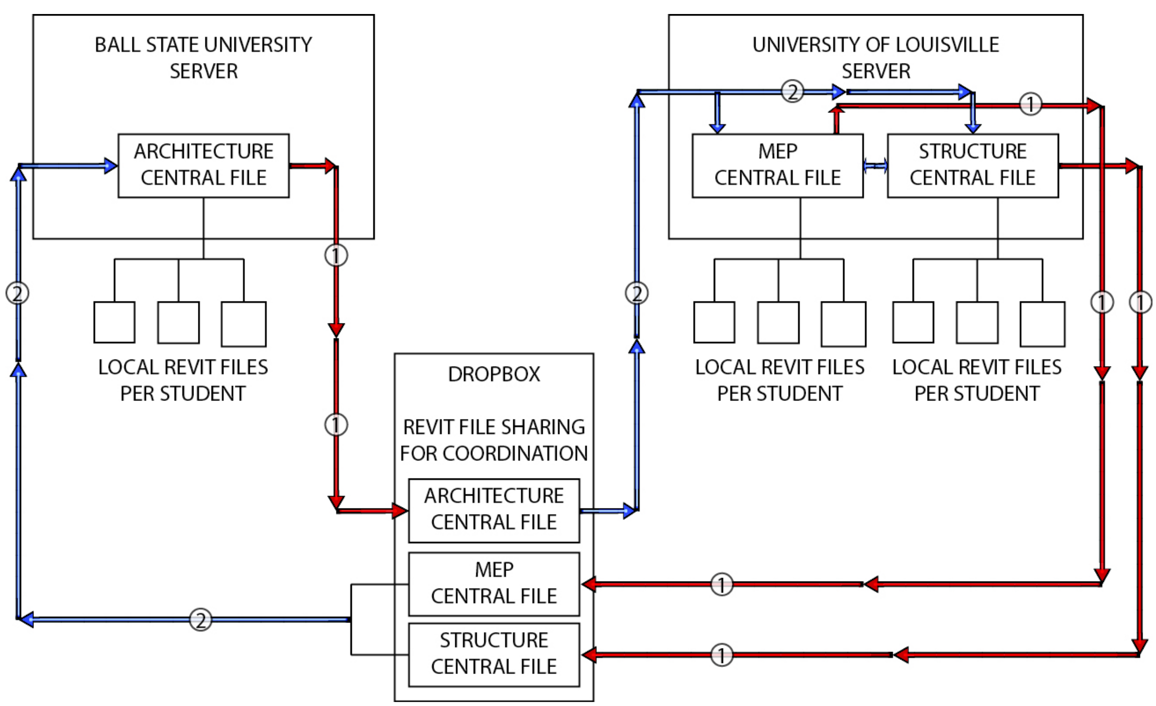


Fig. 2 File sharing organization used by the architecture and engineering teams (1 indicates exporting to the shared model and 2 indicates importing).

input from engineering students, such as the energy analysis, was based on independent calculations based on the current architectural solution. Similarly, cost analyses performed by construction management students used quantities taken from conventional dimensioned drawings. The main challenge was for the engineering students to model mechanical systems and structures in Revit. Initially the engineering students suggested modifications (mostly during verbal discussions) and the architecture students made corresponding changes to the Revit model (Figures 3 and 4). The aggressive Design Development schedule, however, forced the students to adopt BIM as a collaborative method. The construction management students who had to estimate the house cost, received Revit training at the beginning of the fall semester of 2012, only few weeks before the deliverables due date.

The Design Development deliverables required an integrated BIM modeling process and there was a need to assign specific modeling tasks to engineering students working with Revit MEP and Revit Structure. The problems encountered at this juncture may be indicative of the educational challenges in both architecture and engineering schools. The architecture students were able to use Revit as a collaborative tool relatively early in the design process; learning the software and organizing the design according to BIM logic was much more problematic for engineering students.

**3.3 Impressions of BIM**

A survey was administered during the third phase of the design process to evaluate the effectiveness of BIM (among other options) as a collaborative tool. The interdisciplinary collaboration methods that students perceived as most effective were the "Design Weekends" (multi-disciplinary face-to-face design sessions) and “personal interaction.” Only 15% of student respondents listed the shared Revit model as the most important collaboration method. Physical distance, schedule conflicts, and lack of time to interact were seen as the greatest challenges. Significantly, less that half of the architecture students indicated that the Solar Decathlon "greatly enhanced" their understanding of the BIM process, the major obstacles being difficulties in file-sharing management and uneven level of Revit skills among the team. At this stage, architecture students felt that Revit had not greatly contributed to enhancing the project workflow and the creativity of the design. A clear majority agreed, however, that the collaboration with engineering students was essential to achieve the project's objectives (75%), and had led to an increased understanding of the design process (64%). Students also agreed that learning Revit was an important component of their professional training.

The survey discussed above was reissued at the end of fall semester 2012 to see if there were any changes in key impressions regarding BIM and interdisciplinary collaboration as the project progressed and Revit perhaps became more of a norm than a challenge. No substantive shifts in impressions were noted—although the survey return rate in the second round was rather low. It seems reasonable to assume that impressions of BIM and team coordination (relative to this project) remain essentially those expressed through the initial survey.

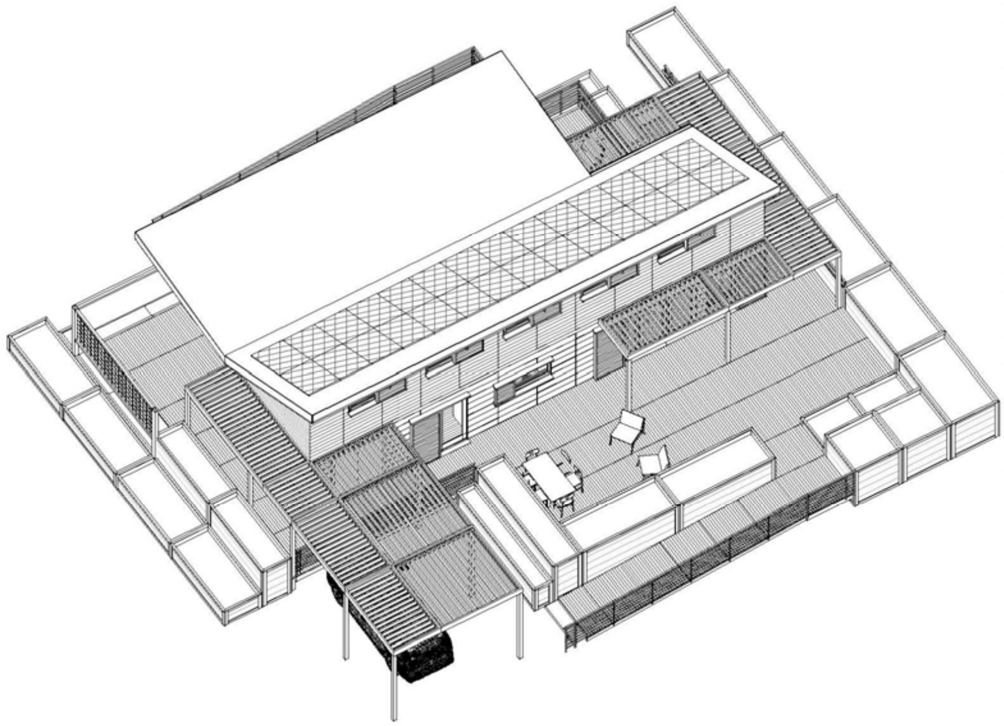

Fig. 3 Axonometric view of Team Kentuckiana house from the Revit Architecture model at an early Design Development stage.

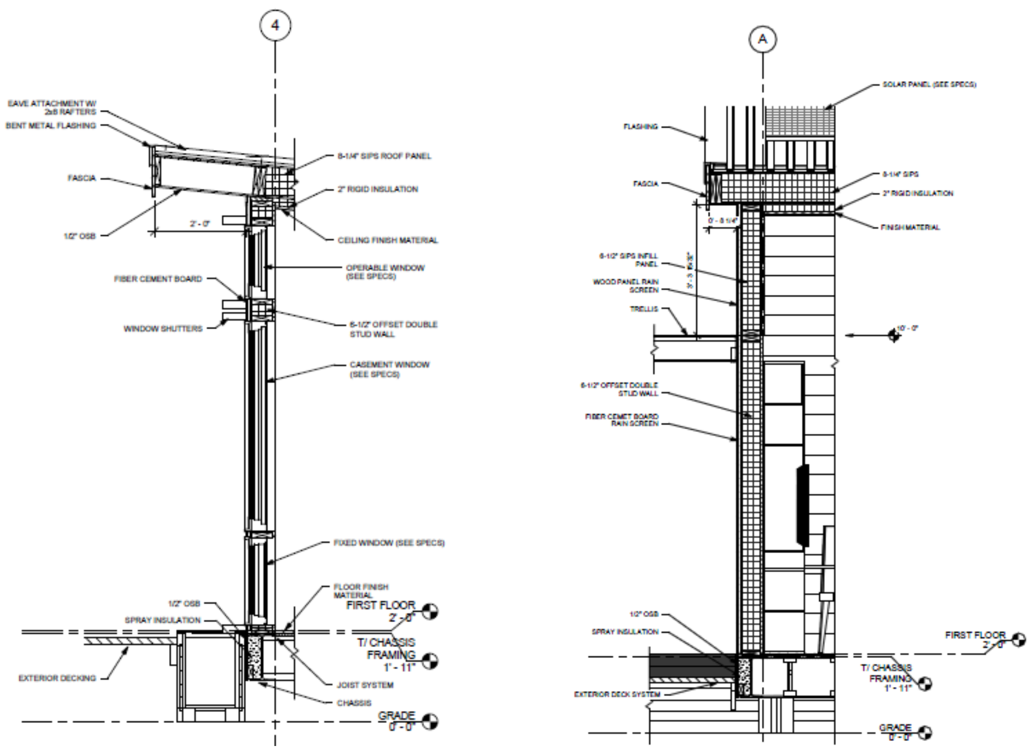


Fig. 4 Wall construction sections generated from the Revit Architecture model.

# 4. CONCLUSIONS

The Solar Decathlon proved to be an excellent vehicle with which to engage integrated design and BIM technology within academia. A desire for success in this diverse and challenging competition provides the need-to-know recognition that often acts as a substantial spur to learning. Understanding the demands of the competition make it clear, early in the design process, that strong collaboration between disciplines is essential for a competitive outcome. The use of BIM is not negotiable. Solar Decathlon teams wishing to compete will cross disciplinary boundaries and use Revit. The inherent nature of the project serves to break down academic traditions and inertia.

Two ongoing questions arise from this experience. Can the strengths of interdisciplinary design become ingrained in our various curricula? Only time will answer this question. What did we learn from this experience? A few thoughts on this follow.

Why was it more difficult for engineering students to adopt BIM? This can be understood first of all by looking at the type of education and design tools used in architecture, where three-dimensional modeling is used from the beginning as a form of visual thinking. Visual thinking is not just a way to represent artifacts to a third party, such as a client, but is a form of creative thinking very different from verbal and mathematical thinking. Architecture students learn early to work with digital modeling in a sophisticated way, and this makes easier to learn new types of three-dimensional architectural modeling software.

Secondly, the attitude of the so-called allied professions (not only engineering, but construction management, interior design, and other professional specializations) is typically to await a detailed architectural solution, so that it can then be “engineered” (or cost-estimated, landscaped, etc.). This leads to a "let’s wait" attitude ("just-in-time") that puts the burden of responsibility on the architecture team, while opening the overall design outcome to potential strategic flaws (e.g., high cost due to complexity in design and difficulty in construction) and design process inefficiencies, resulting from time-consuming changes made when the design is in an advanced state.

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# APPARATUS FOR BUILDING ELECTRICAL SYSTEMS EDUCATION

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## ABSTRACT

This paper describes the design, construction, and use of an apparatus created to enhance building electrical systems education in a junior level Architectural Engineering (AE) course at the University of Nebraska-Lincoln. Electrical systems are a critical part of any building and one of the four major areas in AE education. This hands-on apparatus provides students the opportunity to learn how parts of the electrical system are connected together through the use of three interactive laboratory assignments. Electrical labs were developed to strengthen the technical knowledge of buildings, the engineered systems within, and the integration of these systems in a total building context.

Five electrical boards were created, consisting of a three phase load center, junction boxes, and conduit permanently mounted to a portable board. In order to power the load center, a cord and plug were hard-wired to the lugs of the load center. At the start of each lab, the groups are given circuit breakers, pre-cut wire, receptacles, light switches, light sockets and adequate tools to complete each assignment. The voltage connection assignment consists of installing 1-pole, 2-pole, and 3-pole breakers for different types of loads. The objective is to reinforce the understanding of how different voltages are connected within a 3-phase power distribution system. In the next two assignments the students learn how to properly wire receptacles, a single pole light switch controlling 1 light, and a 3-way/ 4-way switch combination to control multiple lights. The paper includes assignments and a website link to equipment lists.

The reaction to the hands-on electrical labs has been exceptionally positive. The students enjoy applying class learning to actual electrical installations. The electrical labs are flexible and could be used in a variety of ways to reinforce many topics.

Keywords – buildings, education, electrical

## INTRODUCTION

An electrical apparatus was created for the AE3220 Electrical Systems for Buildings course at the University of Nebraska, to help reinforce the understanding of a common building electrical distribution system. AE3220 is a 3 credit hour course offered once each year and is required for all junior-level AE students. The course covers electrical fundamentals, building electrical power systems, building electrical systems design, grounding, transformers, power factor correction, voltage drop and fault analysis. The prerequisite for this course is ELEC 2110 Elements of Electrical Engineering, where students learn the principles of electrical circuit theory. Additional courses in the electrical power option include AE8220 Building Electrical Systems II (3 credits) and AE 8030 Building Communications Systems (3 credits).

The electrical apparatus was developed to provide students a hands-on way to learn all the parts and pieces of a typical electrical system. The three lab assignments teach the students to identify the components of an electrical system, 3-phase loads, and voltages. Students also learn how to wire receptacles, light switches and lights in different configurations.

The electrical apparatus and labs are intended to be used in a controlled environment under the supervision of a knowledgeable electrical instructor. The authors take no liability for the recreation and use of the apparatus/labs.

## DESCRIPTION OF ELECTRICAL BOARDS

The electrical boards were designed to be portable and can be used to teach multiple components of an electrical system. Each board consists of a three phase load center, junction boxes, and conduit permanently mounted to the plywood board (Figure 1).

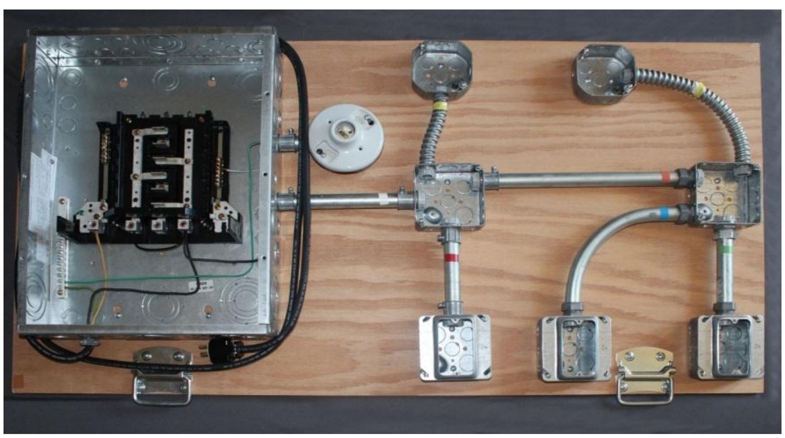


**Figure 1 - Electrical Apparatus**

The layout of the board was determined based on the size of equipment and type of lab assignments. The 3-way/4-way lab assignment required the most components and therefore, the number of components and layout was determined by this lab. Not only is the board used for different assignments, but it is a teaching tool in itself. The board demonstrates different types of conduit, boxes, and fittings that can be found in most buildings. For example, both rigid and flexible metal conduits were used as well as two types of fittings: set screw and compression type. Students also become familiar with junction box sizes, bushings, plaster rings and begin to understand how all the components are used to create a complete pathway for electrical circuits. Another valuable part of the board is that students can begin to identify components inside of the load center such as the lugs, the ground and neutral buses, etc. Finally, the handles you see in the figure above were provided for easy transportation of the boards.

In order to power the load center, a cord and plug were permanently hard-wired to the lugs of the load center. Only two phases of the board, Phase A and C, are powered, refer to figure 2. Choosing which phase to power (all, two, or only one) is a preference based on how the labs will be structured.

**Figure 2 - Load Center**

Safety when dealing with electricity is extremely important, and therefore, safety measures were taken into account. The most important safety factor was the red indicator light that is permanently wired to the power source. The red light is illuminated whenever the load center is plugged in (demonstrated in Figure 3), which allows both the students and the instructor to know when the apparatus is powered. Other safety features include:

- The instructor checks all wire connections before the students secure the devices to the junction box. This includes checking to make sure wires are properly connected to the appropriate wire and physically checking all wires to make sure they are securely fastened to devices and wire-nuts (no loose connections).
- Faceplates and covers are provided for all devices.
- Load center cover shall be securely fastened prior to plugging in the board.
- Circuit breakers shall be turned off when the board is initially plugged in.

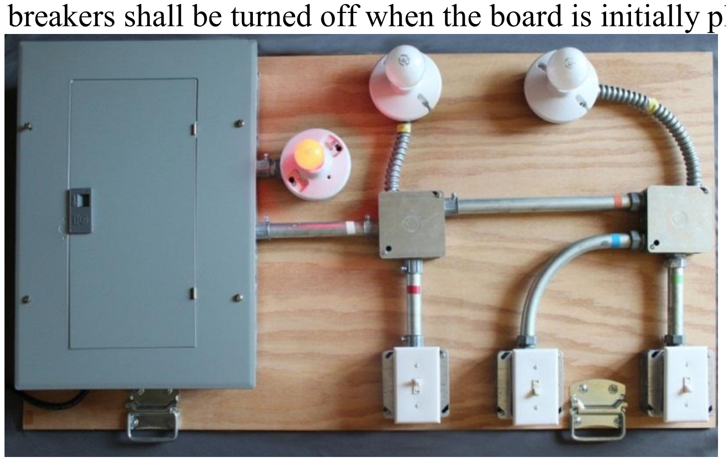


**Figure 3 - Safety Features of the Electrical Apparatus**

The quantity of electrical labs to construct is based on the physical classroom size as well as number of students. Each lab can accommodate three to four students working on the lab at one time. Three is the ideal number of students to allow everyone a chance to be involved in the lab at the same time. Five boards were created for the University of Nebraska.

## DESCRIPTION OF ASSIGNMENTS

Three 1-hour lab assignments were developed for the use of the electrical apparatus. Each lab was designed to reinforce the understanding and technical knowledge of buildings and the engineered systems in a total building context.

**Lab #1: Voltage Connection**
The voltage connection assignment (Appendix A) is the first lab where the students are introduced to the electrical apparatus. Students are required to install 1-pole, 2-pole, and 3-pole circuit breakers and to configure the proper wiring for the voltage connections of the different loads typically found in a 3-phase power system. The students are given the breakers and black, red, blue, white and green wire to complete the lab assignment. The assignment helps students understand how the color coded wire relates to the different phases and are required to identity/observe how components are connected inside of the load center. No power is required for the first assignment, which allows the students to get acquainted to the apparatus and not have to focus on the safety of the electrical component.

**Lab #2: Single Pole Light Switch and Receptacles**
The second lab assignment (Appendix B) consists of wiring a light to a single pole switch and wiring two receptacles (Figure 4). This is the first opportunity the students have to power the load center; therefore, the instructor will want to make sure that all safety measures are taken into account. The reason that two phases were powered comes into play during this assignment. The students are asked to power the light to phase A and the receptacles to phase C, which helps reinforce the different phases of the load center and the color-coded wire.

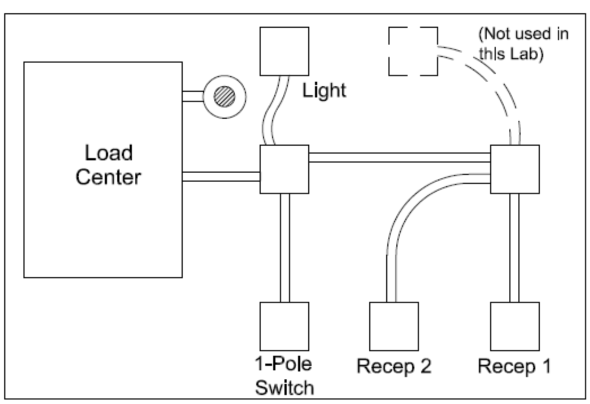



**Figure 4 - Electrical Apparatus Layout for Lab#2**

**Lab #2: 3-way/4-way Light Switches**

The final lab assignment is the 3-way/4-way switch combination to control multiple lights (Appendix C). Learning how to wire 3-way and 4-way switches can be confusing and therefore, this assignment is the most time consuming. The students are introduced to the tracers/switch leg wiring of the devices. As mentioned previously, if the instructor notices that the tracers are connected incorrectly, sometimes the students are asked to walk through their wiring to see if they notice anything prior to securing all the devices and other times the instructor can choose to let the students learn from experience when the switches do not work properly once the lab is powered. It can be a great learning tool either way.

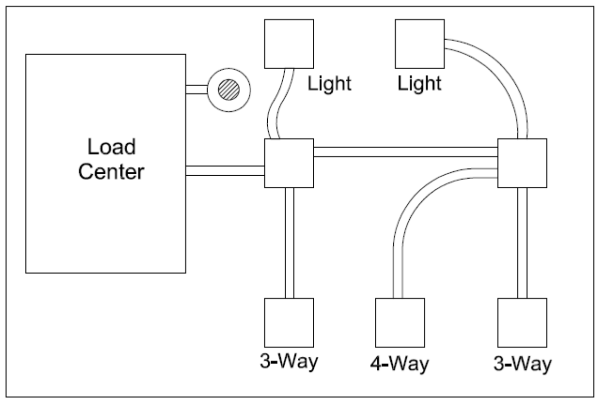



**Figure 5 - Electrical Apparatus Layout for Lab #3**

The following images demonstrate the various stages from start to finish of the 3rd lab assignment.

1. The students are given the board, a bag with all the devices and tools, the circuit breakers, and the panel cover.

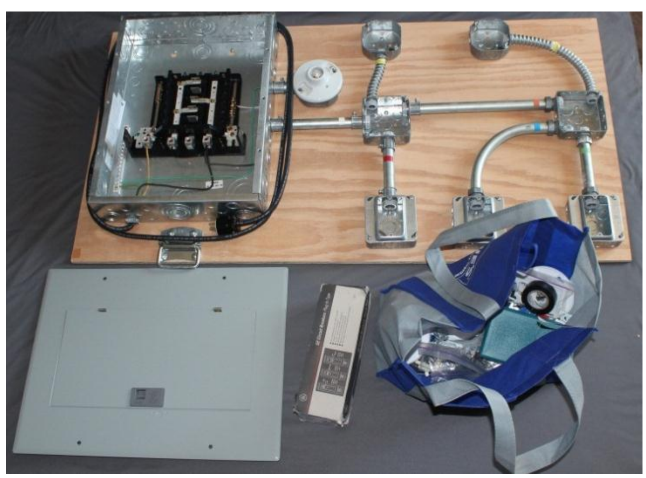


**Figure 6 - Components provided at the start of the lab**

2. The following figure demonstrates all the components required for the lab: circuit breakers, pre-cut wire, light sockets, light switches, faceplates, screws and tools. As shown in the figure, multiple light switches were provided in the bag, which requires

the students to have a greater understanding of the difference between, a single pole switch, a 3-way switch and a 4-way switch.

**Figure 7 - 3-way/4-way lab devices, wire, and tools.**

3. The next image shows all the pre-cut wires have been pulled through the conduit. You will notice that the red safety light is installed but not turned on, because the lab is not powered at this stage.

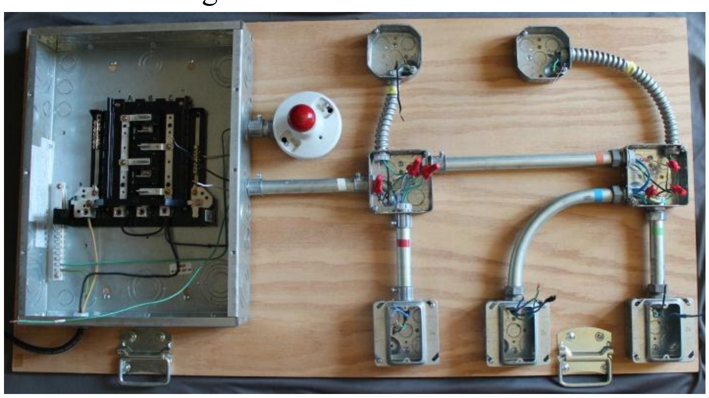


**Figure 8 - Pulled pre-cut wire through conduit**

4. Once the students have connected all of the devices, the instructor checks all connections prior to the students installing the cover plates.

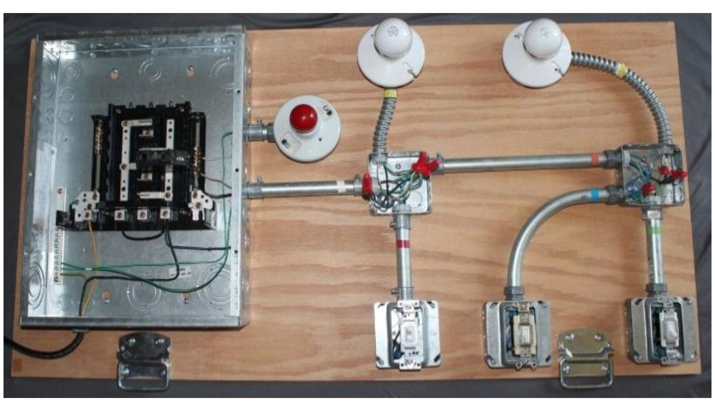


**Figure 9 - Wiring devices installed for instructor to check**

5. Finally, the cover plates are installed and the students can plug-in the load center and see if they have wired the devices properly.

**Figure 10 - Completion of Lab #3**

## LOGISTICAL INFORMATION

The AE3220 Electrical Systems for Buildings meets on Monday and Wednesday for a 50 minute lecture and Friday for a 1 hour and 50 minutes lab period. The lab exercises are conducted on Friday. Approximately 40 students take the course each year and therefore, the class is split in half and divided between the five apparatuses (3 or 4 students each) during the Friday class period.

At the start of each lab, the groups are given circuit breakers, pre-cut wire, receptacles, light switches, light sockets and adequate tools to complete each assignment. A list of materials needed to construct each board, materials needed for each individual assignment and the amount of wire for each assignment can be found on the following website http://www.engineering.unl.edu/durhamschool/faculty-staff/ClarenceWaters.shtml. This information has been provided as a suggested guide to help in the recreation of the electrical apparatus; however, the authors take no liability for the recreation and use of the apparatus/labs. It is the user's responsibility to take the appropriate electrical safety measures.

## CONCLUSION

The student reaction to the hands-on electrical labs has been positive. The students enjoy applying class learning to actual electrical installations. End of the semester evaluation has indicated that this is one of the favorite parts of the course, motivating the students to learn more. The electrical apparatus and exercises provide students the opportunity to learn how parts of the electrical system are connected together in a way that they are much more likely to remember.

# APPENDIX A

Nebraska Lincoln
Architectural Engineering

## Electrical Systems for Buildings
### VOLTAGE CONNECTION LAB
30 points

Group Member's Name: ______________________________________________

**Purposes:**
To reinforce understanding of how building electrical distribution systems are configured.
To reinforce understanding of how different voltages are connected within a building distribution system.
To reinforce understanding of the position of the circuit breakers relationship to phase connection.
To reinforce understanding of grounded and grounding busses and connections.
To observe the difference between trip and fault current ratings.

**Assignment:** Each group of four will be assigned an electrical board and will be given the following equipment:
Circuit Breakers: 1-pole, 2-pole, and 3-pole
Conductors: 12 AWG: Black, Red, Blue, White, and Green
Screw Driver

Five types of common loads with their corresponding voltages are listed below. Your assignment is to connect each voltage to the Panelboard, one at a time, using the appropriate circuit breaker and conductors. The conductors will need to be fed through the conduit and into the first junction box. Before you can move on to the next voltage you need the instructor's approval.

| Voltage | Phase | Electrical Equipment | Instructor's Approval |
|---|---|---|---|
| 120 V | A | Receptacle | ____________ |
| 208 V. 1Φ | CA | 1Φ Motor | ____________ |
| 120/208 V. 3Φ | BCA | Panel Board (Typically not 20A) | ____________ |
| 208 V. 3Φ | CAB | 3Φ Motor | ____________ |
| 120/208 V. 1Φ | AB | Dryer (Typically not 20A) | ____________ |

**Questions:**
1. Look at the grounding buss. How is it mounted to the load center can?
2. Look at the Grounded (neutral) bus bar. How is it mounted to the load center can?
3. Observe the circuit breakers that you are using. Describe the number of poles, the trip rating and the fault current rating of each breaker.

**Deliverable:** Individually provide hand drawn diagrams of the connections of each of the five loads in this exercise and answers to the questions.

**Time Frame:** The Voltage Connection Lab write up is due at the beginning of class one week after the lab is conducted.

# APPENDIX B

Nebraska Lincoln Architectural Engineering

## Electrical Systems for Buildings
### SINGLE POLE SWITCH AND RECEPTACLES LAB
30 points

Group Member's Name: ____________________________________________

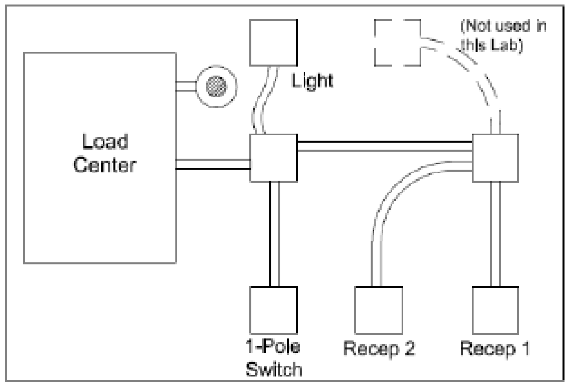
**Purpose:** To reinforce the understanding of how light switches and receptacles are connected within an electrical system.

**Assignment Outcomes:**

1. The *technical knowledge* of buildings, the engineered systems within, and the integration of these systems in a total building context. Specifically, this lab will further the student's knowledge of connecting circuits within the building distribution system.

**Assignment:** Each group of three will be assigned an electrical board and will be given the following equipment:

- Circuit Breakers: (2) 1-pole
- Load Center Cover
- Conductors: 14 AWG Conductors
- 1 Single Pole Switch and Plastic Cover
- 2 Receptacles and 2 Plastic Covers
- 1 Plastic Light Socket and Light Bulb




The figure illustrated above shows how this lab is to be connected. The light should be on a separate circuit than the receptacles:

- Light should be on Phase A
- Receptacles should be on Phase C
- Separate Neutral and Ground for each circuit

**Steps:**

1. Feed conductors through conduit and connect them to the appropriate equipment. At this point **do not** secure the light switch, the light socket or the receptacles to junction boxes.
2. Before you can secure the electrical equipment you must obtain the instructors approval.
3. After receiving the instructor's approval you may continue to secure all equipment and covers.
4. Once all the appropriate equipment is on, please ask for the instructor's approval again.
5. Place the circuit breakers in the OFF position. Then, you may plug in the load center. *Once the panel has power, no team members should touch the any metal equipment. *
6. You may now flip the circuit breakers to the ON position. Ask instructor for the receptacle tester to see if your receptacles are connected properly, and test your light switch.
7. Before you can disassemble the lab, you must show the instructor that you were able to properly connect the light and receptacles.
8. Please disassemble the lab and neatly place equipment where you found it at the beginning of the lab.

**Deliverable :** Draw a detailed connection diagram of this lab. You will be graded on quality, completeness, and presentation.

# APPENDIX C

University of Nebraska Lincoln
Architectural Engineering

## Electrical Systems for Buildings
### 3-WAY AND 4-WAY SWITCHING
30 points

Group Member's Name: ______________________________________________

**Purpose:** To reinforce the understanding of how light switches are connected within an electrical system.

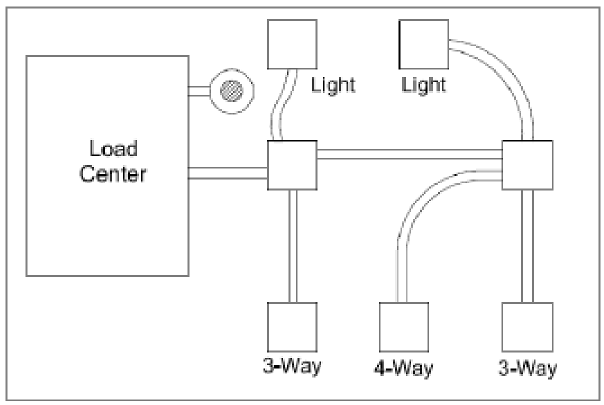
**Assignment Outcomes:**

1. The *technical knowledge* of buildings, the engineered systems within, and the integration of these systems in a total building context. Specifically, this lab will further the student's knowledge of connecting circuits within the building distribution system.

**Assignment:** Each group of four will be assigned an electrical board and will be given the following equipment:

- Circuit Breaker - 1-pole
- Load Center Cover
- Conductors: 14 AWG Conductors
- (2) 3-Way Switches and Plastic Covers
- (1) 4-Way Switch and Plastic Cover
- (2) Plastic Light Sockets and Light Bulbs

Note: The 4-Way switches do not have the insertion hole on the back, therefore, you will use the screws to make your connections.




The figure illustrated above shows how this lab is to be connected. Light circuit will be connect to Phase A

- Use the Blue wire for the tracers.

<u>**Steps:**</u>

1. Feed conductors through conduit and connect them to the appropriate equipment. At this point **do not** secure the light switches or light sockets to junction boxes.
2. Before you can secure the electrical equipment you must obtain the instructors approval.
3. After receiving the instructor's approval you may continue to secure all equipment and covers.
4. Once all the appropriate equipment is on, please ask for the instructor's approval again.
5. Place the circuit breaker in the OFF position. Then, you may plug in the load center. *Once the panel has power, no team members should touch any metal equipment. *
6. You may now flip the circuit breaker to the ON position and test the 3-Way and 4-Way light switches.
7. Before you can disassemble the lab, you must show the instructor that you were able to properly connect the lights.
8. Please disassemble the lab and neatly place equipment where you found it at the beginning of the lab.

<u>**Deliverable :**</u> Draw a detailed connection diagram of this lab. You will be graded on quality, completeness, and presentation.

# SUPPORTING STUDENTS STRUCTURALLY:
Engaging Architectural Students in Structurally Oriented Haptic Learning Exercises

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**ABSTRACT:**
Beginning architecture students have traditionally been taught structural design using an engineering-based educational model. Often, information is presented in formula-rich lectures filled with abstract representations of architectural space. In other words, when structural design is presented as a series of calculations instead of a series of design explorations, educators miss a great opportunity to develop a better integration between structural information and other architectural coursework—and integration that would enhance design development by balancing technical resolution and exploration.

A new educational model for teaching structural design to architects is needed. Architecture students should be given a series of exercises that help to develop their understanding about the relationship between structural form and forces, structural behavior, and the array of potentially responsive architectural forms. This paper will demonstrate how a curriculum based on experiential exercises, haptic learning methodologies and project-based design exercises in a laboratory setting can provide a more effective way forward in educating architects about building structures.

Because initial exposure to complex topics can often make a significant difference in long-term learning efficacy, this paper will primarily discuss the very first lab project in the sequence, an ergonomic lab in which the students use their bodies to explore basic structural principles related to the relationship between form and forces.

**KEYWORDS:** Body Structures, Haptic Learning, Structural Pedagogy

## RESTRUCTURING A STRUCTURAL EDUCATION:
*"The process of visualizing or conceiving a structure is an art. Basically it is motivated by an inner experience, by an intuition."—Eduardo Torroja, 1958*

At its most basic level, structural design is about creating strategies for "spanning and stacking" elements in interesting and effective ways. Although these challenges are elemental, the diversity of acceptably responsive solutions can become a staggeringly complex array of choices—choices that rely upon a broad and balanced set of design skills. Helping architecture students develop the skills to evaluate the pros and cons associated with selecting and arranging different structural choices is, at its core, a process of reiterative design.

Unlike other design courses, however, structural design also needs to impart a more specific technical acumen, often times involving a heavy combination of math and physics, that students need to critically assess and develop their work. However, this often results in a teaching method that primarily emphasizes the importance of quantitative understanding and assessment—it does little to develop the qualitative aspects of structural design related to the interdependence of materiality, form, and structural behavior. Unfortunately, if the teaching methodologies and learning environments in the initial classes aren't effective, this can adversely impact efficacy of retention and enthusiasm for the topic. This problem is more profound in a multi-semester sequence of courses with graduating levels of difficulty, in which there is a necessary expectation of accumulated knowledge and skills from previous courses.

This paper will present the first lab in newly revised undergraduate structural design sequence at Iowa State University, called Structural Technology in Practice (STP). Courses are taught in five-week modules in a combined lecture / laboratory classroom setting for five sequential semesters. In hopes of providing a more effective means for educating architectural students about qualitative and quantitative aspects of building structures, this sequence has integrated a new pedagogical model for teaching structural design by integrating haptic learning methodologies into the coursework. Students are regularly asked to design, build, and sometimes break their structures in an attempt to better demonstrate how structures work and to see structural design as interactive.

During the first class of the new sequence, the *anthropomorphic structures* lab, students use their bodies to explore basic structural principles related to the relationship between form and forces. By constructing lightweight structural conditions, students developed an ability to analyze and describe the structural behaviors their bodies were enduring, including their first conscious exposure to variously intuitively understood structural limitations their bodies navigate daily. In many ways this lab is representative of many of the larger pedagogical goals for the entire sequence—it demonstrates the types of activities that regularly take place within the revised classroom setting, it reveals how these alternative methodologies are used to learn about essential, even traditional, aspects of structural behavior, and it shows how these methods of learning are reinforced in the manner by which students are allowed to represent and discussed their experiences.

## THE FIRST LESSONS & STRATEGIES FOR LEARNING:

There are essentially three main priorities for initial courses in a sequence: teach foundational topics effectively by emphasizing conceptual understanding of behavior, introduce a range of various problem-solving techniques for students to try, and instill a sustained enthusiasm for the topic by presenting the relevance of the information taught in an engaging classroom setting. These challenges are made more profound in math and engineering based courses because the foundational topics are often based on abstract concepts of physical behavior that are primarily demonstrated using a single problem-solving technique (calculation-based proofs), typically in a passive classroom environment where the communication is one-way (non-interactive). When the means of presenting and processing information is too abstract, as it often is in traditional structural design courses, students are unable to visualize the concepts being presented and the relevance of what is being taught is unintentionally obscured. This leads to a fundamental problem. Teaching the behavior of physical phenomena, like structures, without offering students a chance to physically experience it, results in a deficit of understanding about the principles of the subject (diSessa 1993).

Visualization skills are of central importance in structural design, and yet the capacity to imagine the consequences of structural behavior in complex systems without any conscious perceptible experience is extremely difficult—simply put, if one can't see what's going to happen in a structural system, then it's more difficult to design apt response. The initial challenge, then, is how to impart knowledge about these structural behaviors in a manner that enhances the capacity to visualize the potential behavior. One solution is to engage students in simulations of these situations in an effort to enhance their reasoning about the potential physical behaviors in certain situations—these simulation have been shown to be more effective than the use of visual imagery alone (Barsalou 2008). Integrating physical exercises with the course content strives to enhance the relationship between the body and the physical world, in an attempt to develop embodied cognition, which studies have shown help students to better visualize abstract behaviors based on their perceptual experiences (Black 2011).

Processing abstract information while physically manipulating objects is a proven method for enhancing comprehension, so throughout the entire STP sequence, the use of haptic learning techniques has been a matter of central pedagogical importance in both theory and practice (Williams & Franklin & Wang 2003). In nearly every lab, students have built, tested, bent, and often broken their structures in an attempt to better understand the inherent physical behaviors of how the structures work. And yet, at the beginning of the entire sequence there were very few types of structures that we could reasonably have expected students to construct and test in a critical manner. There was one critical exception—the students already intuitively understood the structure of their own bodies quite well, albeit mostly on an intuitive level. The hypothesis was that the most direct way of establishing embodied cognition was to simply ask students to create structures with their bodies.

**STRUCTURALLY SUPPORTING STUDENTS:**

The Anthropomorphic "Body Structure" lab was designed to effectively address the three principle challenges of early course work: how to establish comprehension of fundamental structural topics, how to present alternative problem-solving methods that promote better visualization, and how to teach representations of abstract content in an interactive environment. Students were encouraged to see how the choices they made intuitively about the arrangement of their bodies can reveal critical lessons about complex structural performance and design strategies.

The learning objective was to conceptually connect abstract terminology of structural behavior (e.g., forces, loads, stresses, and states of equilibrium) with the various physical actions undertaken in each scenario. After allowing students to experience certain elemental structural behaviors, and discussing these conditions with them during lab, they were asked to develop multimodal representations of what they experienced (pictures, diagrams, and descriptions) in a lab report. In the lab, they were asked to include information about a broad, somewhat complex interrelated set of elemental structural terms and conditions: loads (dead & live, point & distributed), force vectors (sense, direction, and magnitude of components and their resultant), stress (compressive, tensile, bending, shear, and torsion), states of equilibrium (translational and rotational), and finally how and where each of these conditions was manifest in their body structures.

As a means of simplifying the relatively complicated and infinite series of potentially possible structural conditions, the lab intentionally presented only two simple and easily understandable structural problems to solve: Using only their bodies, students were asked to see *how far they could span* and *how high they could reach*. By being able to successfully complete these modest challenges, students realized that they *already* understood some aspects of structural behavior and that they regularly create effective, responsive, structural forms, even subconsciously in their daily routines. The process of standing, reaching, and holding objects is so common place that students often fail to recognize these seemingly innocuous activities solve the same structural challenges of "stacking and spanning" that all structural designers face.

This seemingly simple scope belies a much more complex set of learning objectives that could only be met by gradually revealing and suggesting several sub-set scenarios within each exercise for students to enact, such as adding more people to each situation, incorporating weights, and/or allowing walls to be used as part of the system. By slightly changing the factors involved, students reconfigured their structural forms that transferred stresses to different components/body parts and often necessitated a different type of connection/grip to make the system stable. In other words, in order to maintain static equilibrium in a system, an integrated range of variables all need to be considered. This is a profound fundamental lesson that is necessary for more advanced structural design work, and it becomes one of the first lessons taught in their entire sequence.

**Figure 1: Adjusting Body Form for Balance**

## TEACHING STABILITY & EQUILIBRIUM:

The concept of static equilibrium is usually taught by showing equal and opposite force vector arrows that represent the loads and resistance in a structural system. These arrows are represented only two-dimensionally so they do little to help students visualize the challenges of maintaining both translational and rotational equilibrium in a three dimensional system. Students quickly realize that actual structural systems rarely have forces that behave in a straightforward manner suggested by the arrows in the diagrams and they look to alternative methods to visualize structural behavior. One of the greatest initial benefits of the Anthropomorphic Lab is that students can instantaneously understand the complicated nature of equilibrium in structural systems by modifying their stances when they attempt to reach high or seek to find a balance in their body weights when they lean forward to reach farther (Figure 1).

In the spanning exercise, students often form chains with their bodies in which one or two other team members will lean out from an anchor point to reach as far as possible. Most of these exercises immediately reveal the importance of balancing the internal forces within a system as the shape of the structure they create often shifts and evolves the further out the team members reach. For example, sometimes when team members are the same weight, the students supporting the other leaning and reaching student will have a very hard time not falling over—in other words, they realized that the center of their combined gravity has passed beyond the line of support. They intuitively modify their structures by leaning back further and/or reducing the length of arm extension.

In one particularly helpful exercise, one student stands in the middle and allows two other students to hang off of each side. The hanging students consolidate their feet with the middle student and slowly reach outward for a dramatically long span (Figure 2). This pose teaches several key lessons about stability: the weight of the hanging students should be relatively balanced or it doesn't work (rotational equilibrium side to side), all the feet need to be grouped tightly together at one point (concurrent forces and rotational equilibrium front and back), and it demonstrates the natural formal rigidity of a triangle in a system (between their arms, torso, and feet). Few students can achieve this pose because of the heightened level of internal stress felt by the center student in their arms. Of course, this becomes a its own lesson as well.

Figure 2: Rotational Equilibrium and Internal Stresses

**STRESSES AND STRAIN:**

The next observation that students usually make is that they "feel" certain forces differently within their body depending upon their configurations. Intuitively they come to realize that in order to maintain "external" equilibrium within a system that certain forces and loads must first be resisted "internally" by using the strength of their legs, arms, and torsos. Again, depending on the scenario, they realize that the weight of their bodies (or props) are the loads in the system and these loads created different types of stresses (compression, tension, bending or shear) depending on the configuration. Some body parts are better equipped to handle different stresses than others, so students intuitively resist bending with their elbows and torsos, compression with their legs, and tension with their hands and arms. As an example, in an attempt to reach high in a column structure, two students often hold a third student in the middle, either on their knees, waist or shoulders—this structure typically fails


Figure 3: Form adjusted to resist buckling

eventually not because the stance of the supporting students is out of equilibrium, but because the compressive stresses accumulate and fatigues the legs of the students nearly to the point of buckling (Figure 3). In later semesters when discussing the need to provide buckling resistance for compressive elements, such as columns, this lesson is brought up as an example.

Other types of stresses, which are relatively abstract in concept but essential in understanding structural behavior, such as moment forces, bending, and torsion are easily demonstrated in the spanning/reaching exercise. The concept of moment force is perhaps most easily taught by simply asking students to hold a weight away from their body at various lengths—obviously the further away the weight is held, the more their shoulder has to generate an internal resisting "moment" to keep their arm from falling down—simple mathematics are introduced here alongside other physical examples of shelf brackets and tree branches to show how certain shapes are designed to be form resistant against these particular types of stresses. When they are asked to reduce the length of their reach in half and comment upon the new type of force, they always respond not only that it is significantly easier, but some students note that the orientation of their arm greatly contributes to the capacity to resist this new bending moment because a bent elbow also allows the bicep to resist the moment force as well (Figure 4). When they are asked to twist the weight using their arm they can feel the affects of torsion. The students intuitively manipulate the overall form of their structures to reduce the amount of moments, and torsion in lieu of relatively pure compressive and tensile forces. This relationship between the types of stresses created and the overall structural system's form become a primary learning objective of the lab and the entire sequence.

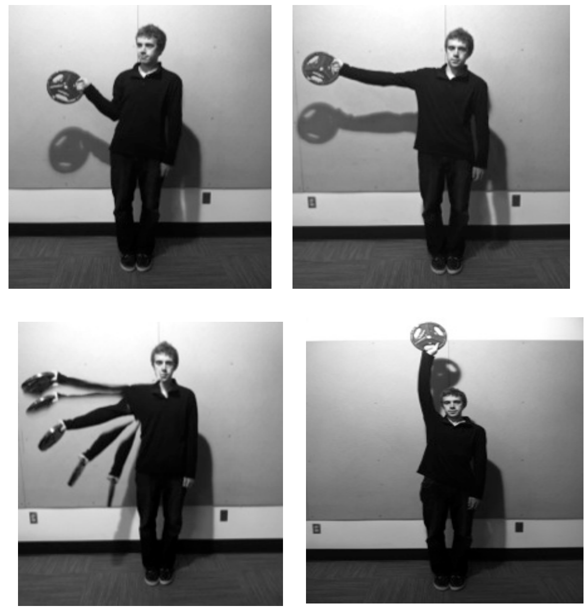

**Figure 4: Moment Force and Lever Arm**

## FORM RESISTANT STRUCTURES:

No matter the exercise, students rarely create any body structures with flat surfaces, right angles, or purely orthogonal arrangements—in fact, in their attempts to create equilibrium in their body structures and minimize the amount of resulting stress on their joints and muscles, the students intuitively create "form-resistant" structural shapes. The shapes, which mimic cable and

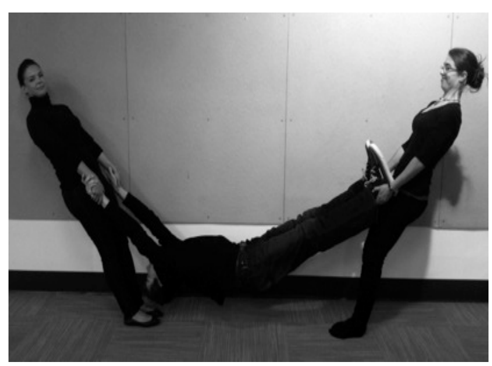

**Figure 5: Form-resistant geometries of the hanging cable and thrust-resisting angle of supports.**

arch structures, are efficient structural design strategies that simplify the stresses within the system to tension and compression by manipulating the overall shape of the structure. This lesson is especially acute with one particular spanning exercise that some students attempt where two students hold up another student off the ground by the hands and feet to create a span as long as the student's body. In doing this, the spanning student's body naturally hangs down in a funicular shape to create complete tension throughout the body. This basic configuration provides an opportunity to talk about axial stresses in a system and the requirement that these types of systems must deal with the resulting thrust in the supports—the two students holding up the middle student often lean back with their entire body, pulling as a means of creating thrust (Figure 5).

Several times students have tried to make a longer "chain," but no student group has been able to lift more than two students at once—the amount of outward thrust needed to lift the structure usually exceeds the students' capacity to maintain their grips in light of the heightened tension throughout the system. With poses like this, it is a great opportunity to talk about structural form and the resulting types and magnitudes of stresses and how they can create specific types of failures associated with these other choices, either a shear failure at connections or a stability failure at the supports.

**SECTION ACTIVE SYSTEMS:**
Finding the particular poses that are well suited to help extract lessons about structural behavior requires that particular poses or variables sometimes have to be enforced. In order to get students to understand the structural difference between form-active and section-active components (such as beams), students often have to be asked to manipulate their bodies to become more "flat" like a beam. Immediately these stresses manifest in their torsos and they find that the human body (particularly it's skeletal frame) isn't particularly efficient in resisting bending at our mid-span! There are some students that try to span between two walls and create a beam between. These students will either: arch their back, cantilever both ends of their body off the wall (to reduce span), try to resist the forces with the strength of their abdomen muscles, or, most interestingly, rotate their torso to the side so it creates a taller cross section (Figure 6). By reducing the span or rotating to the side, they demonstrate the intuitive knowledge that changing the spanning condition and configuring the cross sectional are efficient lessons to resist bending (Underwood 1998).

**Figure 6: In attempting to resist the natural curve suggested by the loading condition, the student feels bending stress.**

**STACKING STUDENTS:**
For the "high reach" exercise, students often build a type of column/pyramid structure with their bodies. This is helpful in several regards. First, these body structures look relatively easy once the students are in their final pose, but the staging of their

"construction" is often quite complicated—there is always a lengthy staging and balancing of students as they construct themselves into their final form. Obviously getting students to think of structures not only as a final static form but instead an articulation of a complicated process of construction. Second, this exercise allows them to visualize and represent the impact that additive loads have on the base of a structure (Figure 7). When students are able to feel how much harder this is with one person on top of another, it is much easier to imagine the increased magnitude of forces and weight that act upon multi-story buildings. And third, the students at the base of the tower or pyramid nearly always triangulate their feet by shifting them forward and backward and side-to-side. Typically this weight shifting is an uncoordinated effort that is often unspoken and intuitive.

**Figure 7: Tower structure involves a coordinated sequencing of erection and eventual reconfiguration of base supports to facilitate the most direct load transfer to the ground.**

For this lab, there are very good opportunities to demonstrate a pinned connection by looking at ankles. Like pinned connections, ankles are designed to pivot with a certain amount of freedom of rotation—humans use this for balance and movement, in structures a similar type of connection is used to let columns move freely without incurring any bending moments. However, if you asked students if they would prefer to have ski boots on during this exercise to stabilize their ankles, many would gladly accept as they realize that this point of connection is a potential weakness of stability.

**MULTI-MODAL REPRESENTATIONS OF ACTIVITIES:**

In the more advanced structural design lessons in the sequence, there comes a time when the calculations and diagrams that describe structural behavior *must* be understood qualitatively and quantitatively quickly. The conventional representations and terminologies are actually quite useful as they describe a series of inter-related, tested, and measured variables that allow for experienced and knowledgeable designers to quickly assess the pros and cons of their design choices. Developing the capacity to have students engage in this level of co-variant reasoning cannot happen unless students feel equipped to understand the concepts behind the formulas and have had experiencing developing their own versions of these types of representations.

Although there is a clear advantage to haptic learning methods which tap into intuitive understanding of structural performance, learning structures by only using one's body has very specific limitations—our bodies can only create a handful of loading arrangements, can only endure a limited amount of stress, and our body forms and gestures can only be used to communicate a small range of structural behaviors. Therefore, as a follow-up to the lab, students were asked to “translate” their personal experiences of structural behavior into representations that employed the more conventional means of representing structural behavior (to the extent that they understood it) in a lab report.

Lab reports are required to address the key learning objectives and questions put forth in the handout, and nearly always include: descriptions and representations of the group’s hypothesis (including early sketches), testing process (including weights and measures as needed), test results (mode of failure), a comparative analysis of results, and a conclusion of what was learned. These early lab reports are relatively open-ended in terms of the type of representations that are required. This flexibility gives students the leeway to experiment with different ways of best representing what they learned. Allowing students to craft a means of representation in support of an argument or as a demonstration of conceptual understanding is important as it gives the students opportunities to diversify their range of learning methodologies. Certain students focus on deductive analysis of particular components while others might use the same exercise but represent what they have learned with a more global learning perspective (e.g., showing how their tower structure was like the Eiffel Tower).

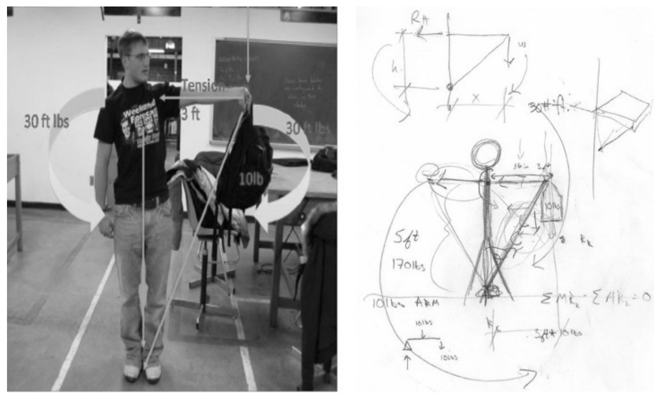


**Figure 8: Sample from a student lab report using calculated force vectors to demonstrate states of equilibrium.**

Students know at the beginning of the lab that they will need to represent the forces they felt—this requirement is included as a way of helping them better visualize the range of experiences they felt. While staging the scenarios, students make notes about the types of forces their bodies feel subjected to and where these stresses were felt. The lab reports are required to include diagrams of force vectors that indicate the type of stresses involved, diagrams of how equilibrium was maintained, and basic calculations of certain components in the system. Their lab write-up must incorporate proper use of structure terminology (loads, forces, stresses, stability, stiffness, strength, etc.) alongside these representations.

**RESULTS & ASSESSMENTS:**

Because only one class of students has completed all five courses of the new sequence and because so many factors have been reconfigured from the previous structures courses (different classroom setting / format, different teacher, new learning methods and resources, new tests/assignments and means of assessment, etc.) it’s difficult to accurately assess the learning results in terms of “before and after” efficacy. However, there is evidence that this first lab was influential not only in establishing a positive learning environment, but that it contributed to a long-term strategy for helping students understand more complex structural behaviors.

Student evaluations for the new sequence been consistently higher than those for the previous courses, including markedly higher scores for questions asking students to assess how much they felt they learned, whether or not they felt the course was important to their education, and an overall assessment of the course's quality. Motivation also seems to have been improved. In the comments portion of the evaluation for this particular module, students frequently praised the interactive nature of the classroom and oftentimes mention the first laboratory as a positive (and often "fun") first experience.

Labs completed in subsequent semesters of the structural sequence showed an advanced level of comprehension of basic structure concepts and behaviors, along with more advanced abilities to create multimodal representations of these behaviors, including models, images, sketches, and written descriptions of experienced physical phenomena—as a result, the comprehensive design studio now occurs in conjunction with the final course in the sequence (in the fall of their fourth year)—a full year earlier than before the sequence was initiated. Later coursework also showed the lasting influence of this first lab. In the final module, students were assigned a comprehensive case study that included models, drawings, and written descriptions. Several different teams made frequent references, both in their descriptions of behavior and modes of representations, to the "body structure" as a way of explaining their conclusions.

One of the fundamental goals of this first lab, and the new structural curriculum sequence, was to help students realize that structural design is an accessible, exciting, and important component in architectural design. These first lab exercises provided a cognitive grounding in basic structural behavior (transferring knowledge from the abstract into more tangible realm) and presented a methodology for self-taught examination, analysis, and representations of basic structural concepts. The results suggest that one of the ways of developing a better conceptual understanding of basic structural behavior is to emphasize the importance of embodied cognition in interactive classroom environments. While it is not a direct reflection of improved student learning effectiveness, the course received a 2013 ACSA Creative Achievement Award.

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# QUANTIFYING THE IMPACT OF OCCUPANT BEHAVIOR IN MIXED MODE BUILDINGS

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## ABSTRACT

As systems in high performance buildings become more complex and manually operable windows and shading devices are incorporated into advanced buildings, it is imperative that building engineers understand and account for the impacts that occupant behavior may have on building performance. By coupling building energy simulation models with stochastic occupant behavior models, the magnitude and distribution of impacts that occupants have on building energy consumption are demonstrated via a simulation study. The results show that occupant actions can increase or decrease energy consumption depending on the HVAC control strategy implemented. For a single month during the cooling season, the range of HVAC electricity consumption predicted by a set of simulations that included stochastic models of occupant window, blind, and lighting use varied by approximately 20% for each of 25 different control scenarios.

Keywords: building energy use; mixed mode buildings; occupant behavior.

## INTRODUCTION

### Motivation

As energy consumption rates increase globally, it is of paramount importance to seek innovative and effective methods for decreasing energy demand and increasing efficiency. In the United States, building energy use accounts for over 40% of all energy use nationwide, and is split roughly in half between the commercial and residential sectors (Energy 2010). Clearly, any reductions in building energy use or building energy efficiency can have a significant impact on national energy demand and associated security risks. High performance buildings have emerged in the last several decades as an effective means of reducing energy demand. One subset of high performance buildings, mixed-mode (MM) buildings, are an attempt to bridge the gap between older, more passive building paradigms with new low-energy cooling and heating approaches, with the intent to provide superior occupant comfort while conserving energy by taking advantage of passive conditioning opportunities.

## Mixed Mode Buildings

"MM refers to a hybrid approach to space conditioning that uses a combination of natural ventilation from operable windows (either manually or automatically controlled), and mechanical systems that include air distribution equipment and refrigeration equipment for cooling." (Brager 2008) Control of MM buildings is typically categorized into one of three approaches: concurrent, changeover, or zoned control. In zoned control, a building is divided into different space types and certain zones are conditioned with natural ventilation while others employ conventional compression based air conditioning (AC). In changeover control, a given zone will have the means to use both conventional AC and natural ventilation, and switches between them such that when one system is in use, the other is off. In concurrently controlled MM buildings, both natural ventilation and mechanical ventilation are allowed to occur simultaneously. This third type is potentially the most risky design because without proper control sequencing it can easily lead to over-consumption when HVAC systems try to heat or cool a space that is not isolated from the outdoors. MM buildings typically incorporate a range of high-performance features (e.g. radiant heating and cooling, active or passive shading systems, and geothermal heat exchangers), and manually operable systems (e.g. windows, blinds, and lights). It is with the knowledge that MM buildings are complex, dynamic, and difficult to effectively control that this paper seeks to evaluate more robust control strategies.

MM buildings have been shown to increase occupant satisfaction, higher indoor air quality (IAQ) and occupant comfort. (Brager 2008) This increased satisfaction is often due to occupants' access to operable features such as windows, shading devices, and lighting systems in their working environment. Recent studies have shown that occupants with access to operable windows typically experience greater comfort across a wider band of indoor conditions. (Nicol & Humphreys 2010; de Dear & Brager 2002). The introduction of operable features in a building leads to considerable uncertainty in the performance of the heating, ventilating, and cooling (HVAC) system. Occupant presence and occupant actions on building systems (e.g. windows, blinds, and lights) change the internal loads of the building and thus the conditioning requirements.

## Models of Occupant Behavior

Studies conducted on identical buildings have shown discrepancies in energy consumption due to occupant behavior ranging from 37% to as much as 600% (Baker & Standeven 1996; Gill et al. 2010). It is difficult to measure precisely when and how occupants will take actions to modify their working environment, but several studies (Reinhart 2004; Page et al. 2008; Yun & Steemers 2008; Hunt 1980) have led to detailed behavioral models that accurately simulate occupant behavior in buildings. Controlling building systems in concert with occupant actions is a challenge due to the stochastic occupant-driven processes constantly changing the building's electric loads and conditioning requirements.

The most fundamental occupant behavior in buildings is simply the state of being absent or present; typical building energy modeling tools use schedules of occupancy that assume consistent and repeated occupancy patterns throughout the year. Several stochastic models for predicting occupancy in buildings have been developed (Page et al. 2008; Wang et al. 2005; Yamaguchi et al. 2003), and for this study the algorithm developed by

(Page et al. 2008) is used to generate annual schedules of occupancy. For each simulated occupant in the building energy model, an annual Markov chain of binary absence/presence is generated at 15-minute resolution, and includes both short and long periods of absence and presence throughout the year.

Occupant actions on operable windows have the greatest impact on the ventilation requirements of a space, and thus models of occupant window use are being developed with increasing frequency. A comprehensive review of occupant behavior models relating to window use is given in (Roetzel et al. 2010), and one of the more recent and most robustly validated models, developed by Haldi et al. (Haldi & Robinson 2009), is chosen for this study. This model of occupant use of windows comes with several 'tuning' parameters to accommodate occupants with different (active and passive) habits, as described in (Robinson & Haldi 2011); the set of coefficients corresponding to the average response is employed for this study. Models for occupant use of shading devices are limited, and again the model developed by Haldi et al. ( Haldi & Robinson 2010) has been selected for use in this investigation. This shading use model predicts first whether a shading device will be acted upon, and subsequently predicts the extent to which the device will adjusted. Blinds are assumed to be either fully opened or fully closed whenever a raising or lowering action is predicted.

As it often represents a large portion of a building's energy demand, and it is typically the low-hanging fruit for increasing energy efficiency, lighting has been the subject of detailed investigations for much longer, with studies and models of behavior being developed over the last 30 years (Hunt 1980). A widely accepted model for occupant use of lighting systems was developed in (Newsham et al. 1995), and has since been revisited and improved, resulting in the Lightswitch2002 algorithm (Reinhart 2004).

While this review focuses on a small sample of what is believed to be the current state-of-the-art behavioral models, it must be noted that other models will likely lead to different metrics for energy consumption and occupant comfort.

## Stochastic Model Predictive Building Control

Model predictive control is a method of process control, normally implemented in discrete time by implementing the following three steps. First, a process model is used to predict over a finite horizon the response and future states of the process given a control input or other perturbation. Second, optimal control sequences are computed to minimize some cost function associated with the process. Third, a portion of the beginning of the optimal control strategy is implemented and, once fully executed, the controller begins predicting and optimizing again, iterating through each subsequent time step.

Stochastic model predictive control extends deterministic MPC to more unstable and non-linear processes, in particular those processes that are subject to stochastic disturbances and variations in inputs or outputs. The defining feature of stochastic MPC (SMPC) is that the controller is presented with a range of possible system responses, and delivers a control strategy that is *very likely* to bring the system to a given state in the presence of stochastic influences, while (conventional) MPC assumes perfect knowledge of the system and delivers a single control strategy (with a single predicted response) which may not be robust to the full range of possible system dynamics.

## METHODOLOGY

To realize control strategies that are robust to the vagaries of occupant behavior in buildings, the range of effects that occupant behavior has on building performance must be quantified, and the quality or inferiority of a given control strategy in the presence of said effects must be measured. The approach given here takes three steps to build towards SMPC; first building occupant behavior models are coupled to the building model and the effects of occupant behavior in the building model are observed. Next, a range of control strategies are applied to a building and the varying degree to which each control strategy is affected by - or immune to occupant behavior is observed. Results for these first two steps are presented in this article. Currently, an architecture for implementing SMPC in a simulation environment is under development, which will enable the discovery of near-optimal control sequences, which can then be used to train regression models and converted into usable building control logic, as proposed in (May-Ostendorp et al. 2011).

To measure the impact of occupant behavior in buildings, the Building Controls Virtual Test Bed (BCVTB) is used to couple the occupant behavior algorithms written in Matlab to objects in the building energy model built in the simulation program EnergyPlus as shown in Figure 1. Simulations conducted within this framework differ from standard EnergyPlus simulations due to the inclusion of stochastic effects in the occupant behavior models; each time a simulation runs, the stochastic models simulate a different occupant behavior, changing the thermal gains and ventilation requirements in the building.

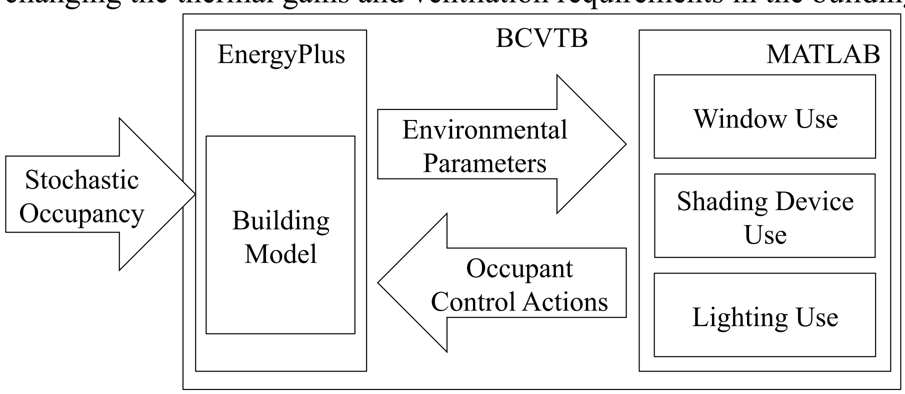


Figure 1: Building Energy Model and Occupant Behavior Model Connections.

In general, occupant behavior models provide a probability at some instant in time of an occupant taking an action; the probability of an action $P_A$ is computed as a function of some combination of current ambient conditions ($C_{Env}$) and occupant characteristics ($Occ$).

Equation 1 $$P_A = f(C_{Env}, Occ)$$

Given this probability and a randomly generated number ($R_U$) from the uniform distribution on the interval $[0,1]$, the two numbers are compared to determine whether the action $A(t)$) takes place or not.

Equation 2 $$A(t) = \chi(P_A > R_U)$$

where $\chi(\cdot)$ is an indicator function that equals 1 if the statement in parenthesis is true. Choosing a threshold value instead of a random variable for comparison leads to a deterministic model of behavior, one in which every simulation would return identical sequences of behavior and thus energy consumption. When stochastic models are employed in simulations, they lead to uncertainty in simulation results, thus multiple simulations must be conducted to arrive at a representative distribution of results.

## Building Model

For this simulation study, an 11 zone EnergyPlus building model representative of a small mixed-mode office building is used. The roughly 1800 m$^2$ (18000 ft$^2$) model is pictured in Figure 2 below and includes manually operable windows, window shades, and lights. The MM model is derived from the DOE reference small office building model, and draws its base features and characteristics directly from the reference model; construction details are consistent with energy efficiency standard ASHRAE 90.1, the only building-controlled MM feature is building controlled windows. The building is oriented such that the longer exterior walls face North and South. The first level is divided into four perimeter zones and one core zone, while the upper two levels are divided into three zones: narrower zones on the east and west facades, and a large central core zone spanning the width of the building.

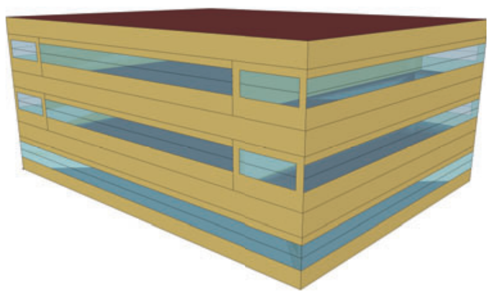

Figure 2: Isometric View of Building

Table 1: GEV Fit Parameters

| Parameter | Estimate | Std. Err. |
|---|---|---|
| $k$ | 0.0214 | 0.0403 |
| $\sigma$ | 95.52 | 4.039 |
| $\mu$ | 4825 | 5.449 |

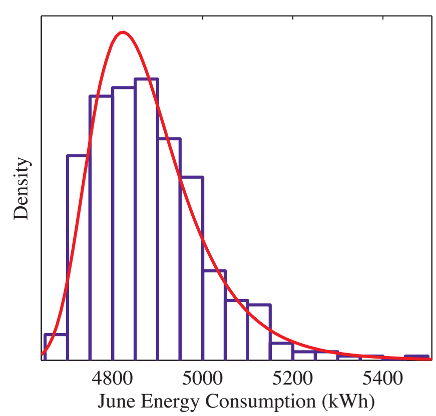


Figure 3: Distribution of Energy Consumption for 400 Samples of Window Opening Behavior.

Occupant density, lighting density, and plug loads are 0.0538 (persons/m$^2$) 10.76 (W/m$^2$), and 8.07 (W/m$^2$) respectively. A conventional gas-fired heating system and direct expansion cooling systems serve the heating, ventilating, and air-conditionings needs of the zones through variable air volume terminal units when natural ventilation is not appropriate. Typical meteorological year data for Boulder, Colorado is used an all simulations.

## RESULTS

Figure 3 shows the results of 400 simulations using the building model described above coupled with the model for occupant use of manual windows; it shows the variation of building HVAC energy consumption for the month of June including the effects of manual window use. In this case, the deterministic simulation (without occupant behavior models - all occupant windows closed) resulted in an energy consumption of 4581 kWh, and the average result of the stochastic simulation (with behavioral models) is 4882 kWh. Note that the resulting distribution of energy consumption is skewed to the right, indicating that the response of the building to occupant actions is not normally distributed, and that occupant action can lead to cost penalties or cost savings compared to the deterministic case (or to the average result of the stochastic case). The long right tail on the data shows that occupants can incur larger energy consumption penalties than they can savings; if the distribution had a long left tail, it would indicate that the opportunity for savings from occupant interaction is much greater than the risk of penalties. While the 6% difference between deterministic and stochastic results appears small, the second value comes with richer information: a lower and upper limit defining a range of what energy consumption could be, and most importantly a high level of confidence in the average result. A generalized extreme value distribution was fitted to the data; the shape $k$, scale $\sigma$, and location $\mu$ parameters for the distribution are given in Table 1.

Figure 4 shows data similar to that in Figure 3 for 25 unique BAS-window control scenarios to demonstrate the dynamic response of the building and occupants to different building control methods. Recall that the building energy model has two banks of windows; the lower bank is assumed to be occupant-controlled (OCC), and the upper bank is controlled by the building automation system (BAS). For simplicity, the various BAS window control scenarios are defined as a single window opening event with two defining parameters: opening time and duration; this entails a single control action that is repeated by the BAS on each day for the duration of the simulation. Five unique opening times (8, 9, 10, 11, and 12:00) and five opening durations (1-5 hrs) represent the assumed set of possible BAS-window control options, resulting in a total of 25 options. For each control option, 400 simulations were completed, so the results presented in Figure 4 are the product of 400x25 = 10,000 simulations.

Note the location of the vertical line in Figure 4 (indicating the result of a deterministic simulation) relative to the distribution of results from stochastic simulations; the bottom row of plots for examples shows that when BAS windows are opened for one hour, occupant actions lead to higher energy consumption than the deterministic simulation predicts.

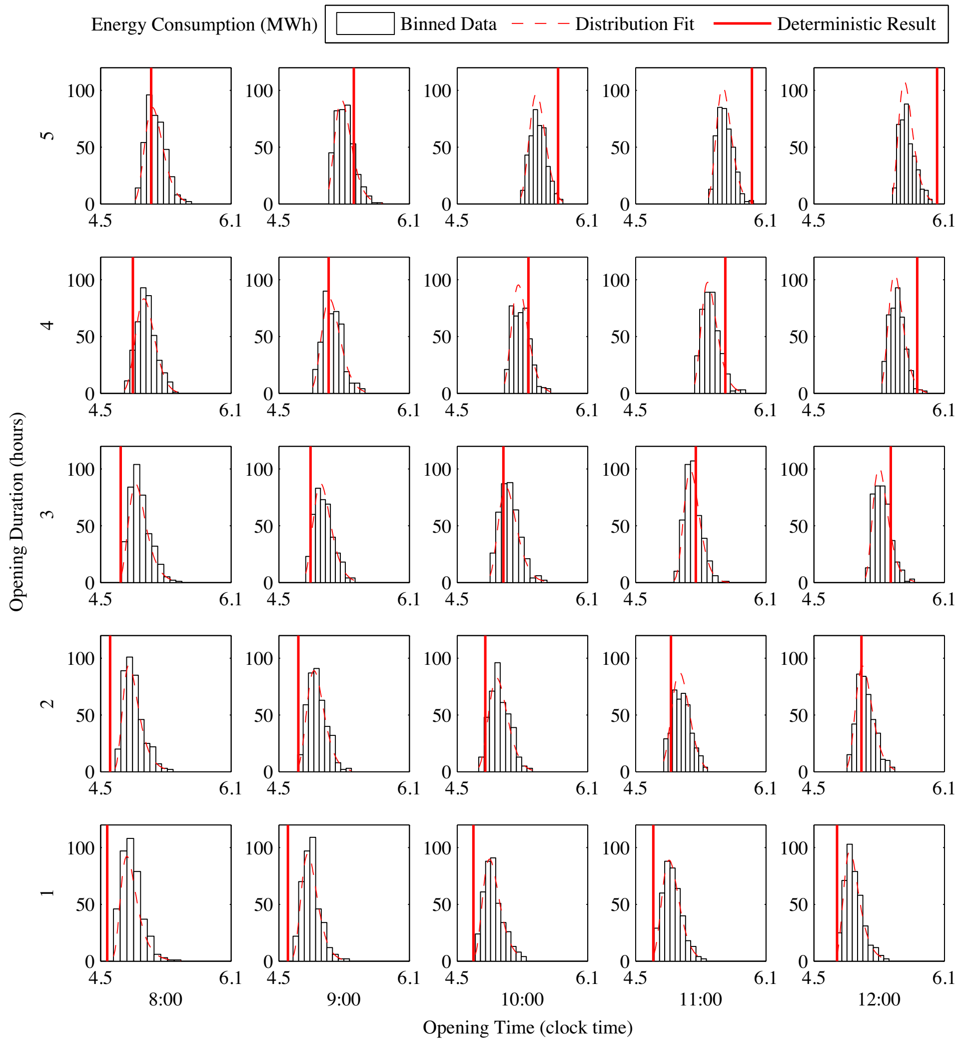


Figure 4: June Energy Consumption for 25 Control Options.

When the BAS window signal commands windows to open at 11:00 or 12:00 for 4 or 5 hours (top-right), occupant behavior leads to lower simulated energy consumption than what is predicted by a deterministic simulation without occupant models. In contrast, in the lower-left quadrant of the figure, the deterministic result is significantly lower than the results predicted by the simulations that incorporate stochastic behavior. For this window control scenario depicted in Figure 4, while the stochastic cases reveal significant distributions of energy consumption for each individual control option, the range of energy consumption between the minimum and maximum mean (5.0-5.7 MWh) is smaller than the range of energy consumption of the deterministic case (4.6-6.0 MWh). For this analysis, occupant behavior compresses the range of building energy use, dampening the effects of the BAS window controls. Looking at the figure as a whole, note the general trend from left to right and from bottom to top (opening BAS windows for longer periods, later in the day) of an increase in energy consumption. This makes sense in the month of June, when opening windows in the afternoon may allow warmer air into the building, thereby increasing cooling loads. In the central plot in Figure 4, there is good agreement between the average stochastic result and the single deterministic result, which is strictly coincidental; for the particular time period of the simulation and the building and occupant behavior models used in this study, when BAS windows are opened at 10:00 for 3 hours, occupant behavior does not shift average energy consumption up or down from the deterministic baseline.

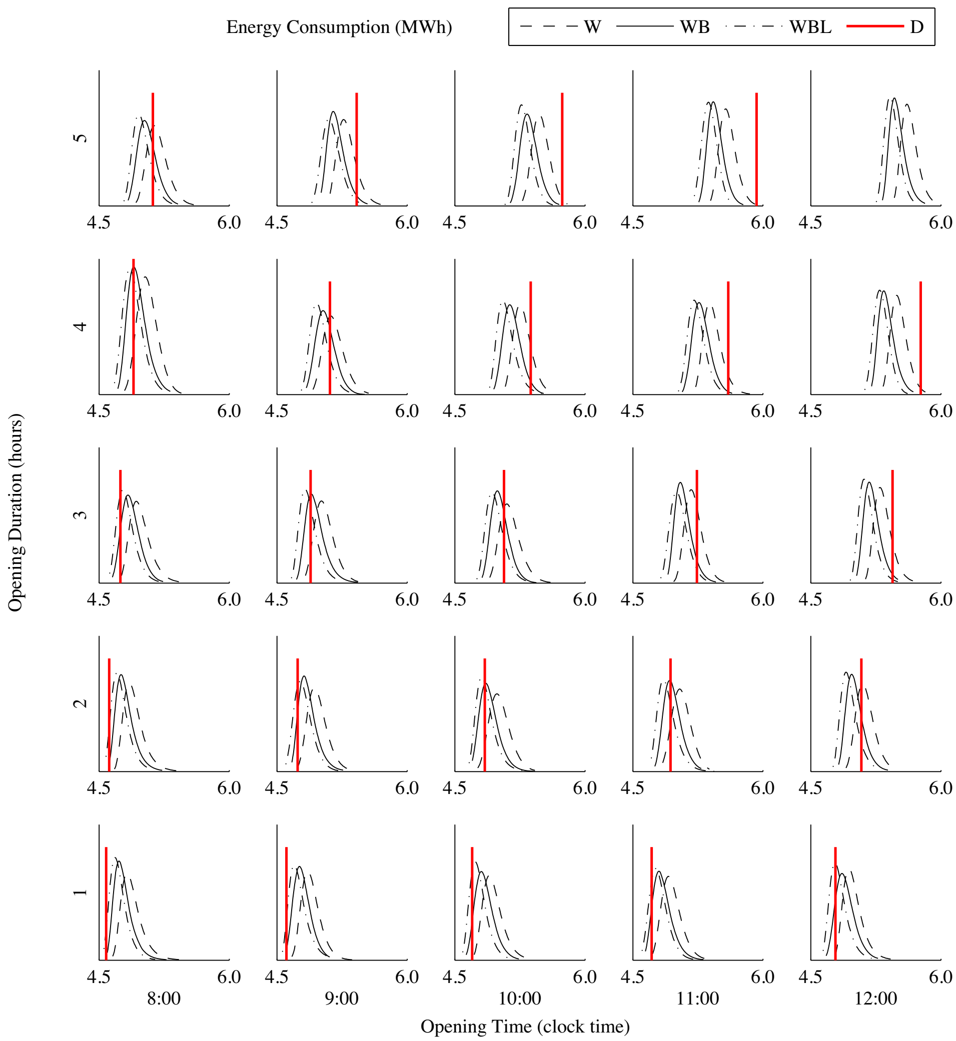


Figure 5: Energy Consumption for 25 Control Options Considering Occupant Use of Windows, Blinds, and Lights.

Figure 5 shows the effects of including additional behavioral models in a suite of simulations just as in Figure 4, however here four different building cases were included: a deterministic case (D), a case which includes the stochastic window use model (W), a case that includes use of windows and blinds (WB), and a case that includes models for window, blind, and lighting use (WBL). Each of the four cases is identical to the others with the exception of the set of behavioral models included.

Two observations are made: First, in all cases, the inclusion of more behavioral models leads to lower energy consumption; the WBL cases use less energy than the WB cases, which use less energy than the W cases. Second, in some cases the deterministic energy consumption is significantly lower, in others significantly higher, and yet in others it is similar to the occupant influenced scenarios, so it can not be assumed that the inclusion of stochastic behavior always leads to decreased energy consumption when compared to deterministic simulations.

Given the results presented in Figure 3, Figure 4, and Figure 5, it is clearly difficult to predict exactly what the net effect of occupant behavior in a building will be, especially for a range of different control scenarios issued from a BAS. This fact leads us to propose the development of methodology for determining near-optimal control rules for buildings that are sensitive to occupant interaction. Work currently underway is thus concerned with developing such an optimization environment.

## CONCLUSION

An investigation of the effect of occupant behavior in buildings on building HVAC electricity consumption was conducted. The results show that occupant actions can increase or decrease energy consumption depending on the HVAC control strategy implemented. Additionally, it is shown that as more models of occupant behavior are added to the energy model, the predicted energy consumption tends to decrease, indicating that added access to manually operable systems and occupant actions on those systems are likely to reduce energy consumption. For a single month during the cooling season, the range of HVAC electricity consumption predicted by a set of simulations that included stochastic models of occupant window, blind, and lighting use varied by approximately 20% for each of 25 different control scenarios.

## ACKNOWLEDGMENT

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# PROBABILISTIC IDENTIFICATION OF INVERSE BUILDING MODEL PARAMETERS

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## ABSTRACT

Probabilistic and nonlinear least squares parameter estimation methods are evaluated for inverse gray box model identification of a retail building. A detailed building energy simulation program is used to generate surrogate data for estimation of parameters. The most probable or optimal parameters from each method are compared through simulation of building zone temperature and thermal loads. The least squares method generally found solutions near probable regions of the posterior from the probabilistic approach, and simulation performance was very similar between best parameter sets. A brief overview of probabilistic estimation techniques is provided, along with potential improvements to the approach presented and brief discussion on its applicability for uncertainty quantification within the building science domain.

## INTRODUCTION

Advanced building control and fault detection methods utilize building energy models to forecast or estimate expected building performance. Online implementation of such methods requires computationally efficient models that capture the critical system dynamics. Inverse gray box models have shown the potential for blending the benefits of building physics knowledge and performance measurements by allowing physically-based model parameters to be estimated from measured data. Inverse gray box building models have been successfully used to forecast cooling loads and energy consumption for optimal control strategy evaluation (Braun & Chaturvedi 2002, Braun et al. 2001, Zhou et al. 2008). Extended Kalman Filters (EKF) have also been incorporated to improve real-time load estimates using available building automation system (BAS) data (O'Neill et al. 2010).

Various model identification techniques have been demonstrated that typically involve time or frequency domain least squares minimization via traditional (e.g. Gauss-Newton) or metaheuristic (e.g. genetic) algorithms. These traditional methods typically result in point estimates of the parameters without consideration of parameter and data uncertainty. Additionally, these methods are often sensitive to initial optimizer seeds and starting conditions. Lauret *et al.* demonstrated improvements over traditional parameter estimation

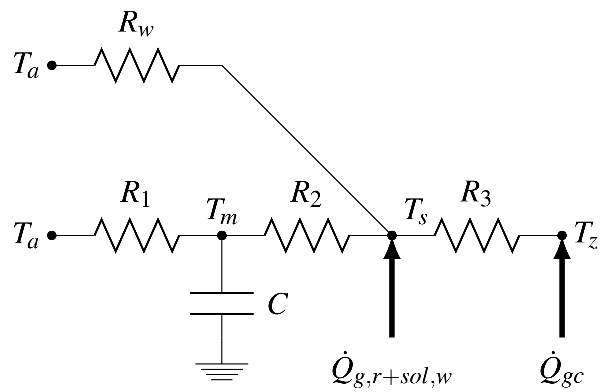


Figure 1: Five-Paramater Thermal RC Network

methods through the application of Bayes's Theorem to determine better estimates of convection coefficients for a radiant barrier roof system model (Lauret et al. 2006). This paper applies Bayesian parameter estimation to inverse gray box building models and provides performance comparisons with traditional least squares point estimates.

## DETAILED BUILDING MODEL

The detailed building simulation program EnergyPlus (USDOE 2011) was used to generate surrogate data from a five zone retail building. The five-zone retail building model was chosen for its relative simplicity and ability to be abstracted to a single zone approximation reduced order model. Furthermore, only hourly sensible zone loads from the detailed simulation are used as the surrogate data for the inverse gray box model.

## REDUCED ORDER BUILDING MODEL

Inverse gray box models are based on the approximation of heat transfer mechanisms by an analogous electrical lumped resistance-capacitance network. For this work, a five-parameter model based on the RC network used in the ISO 13790 "Simple Hourly Method" (ISO 2008), shown in Fig. 1, was used to forecast summer cooling loads for a retail building.

## LEAST SQUARES PARAMETER ESTIMATION

As a first approach to model identification, sum of squares minimization was used to identify model parameters that minimize the root-mean-squared error (RMSE) between the reduced order model forecasts ($\dot{Q}_{rom}$) and surrogate ($\dot{Q}_{ep}$) sensible zone load time series. A two-stage optimization was implemented that first performs a direct search over the parameter space to identify a starting point for local refinement. The direct search is performed on $p$ uniformly random points located within the bounds of the parameter space.

The local refinement, subject to the same parameter constraints, is performed via nonlinear least squares minimization implemented using the Matlab optimizer `lsqnonlin` based on trust-region Newton methods (Matlab 2011). Parameter bounds were set to constrain the solution space to physically plausible values. Parameter bounds can also be slightly relaxed to incorporate geometry and construction uncertainty as well. For this study, 500 direct search points were usedand the least squares parameter estimation was repeated 2500 times, beginning each iteration with a new set of randomly generated direct search points.

## BAYESIAN PARAMETER ESTIMATION

The Bayesian approach benefits over traditional methods because prior knowledge of the system is directly incorporated into the estimation task. The prior probability distribution is updated with any measured data to form the posterior probability distribution, which represents the state of knowledge in any inference task. Specifically, conditional probabilities are related through the product rule to derive Bayes's Theorem (1) and allow consideration of "before data" and "after data."

$$p(A|B) = \frac{p(B|A)p(A)}{p(B)} \tag{1}$$

From a parameter estimation perspective, the probability of parameter set $\Theta$ given measured data $D$ and a knowledge base of the system $K$ can be written as posterior probability $p(\Theta|DK)$. Bayes' Theorem then allows the conditional probability $p(\Theta|DK)$ to be computed from $p(\Theta|K)$, $p(D|\Theta K)$, and $p(D|K)$ as in (2),

$$p(\Theta|DK) = p(\Theta|K)\frac{p(D|\Theta K)}{p(D|K)} \tag{2}$$

where $p(\Theta|K)$ represents prior knowledge about parameter values, $p(D|\Theta K)$ represents the likelihood of observing the measured dataset $D$ given a particular parameter set $\Theta$ and knowledge of the system $K$, and $p(D|K)$ is the probability of observing the dataset. The relation can be written in alternate form where the numerator remains the product of likelihood and prior, and the denominator is a normalization factor so that posterior probabilities sum to unity.

$$p(\Theta|D) = \frac{p(\Theta)p(D|\Theta)}{\sum\limits_i p(\Theta_i)p(D|\Theta_i)} \tag{3}$$

Assuming random Gaussian noise about a measured datum $D_i$, the probability of an observation can be determined from its location within the normal distribution centered at $\mu$ equal to the measured datum, with standard deviation $\sigma_\varepsilon$.

$$p(D_i|\Theta) = \frac{1}{\sigma_\varepsilon\sqrt{2\pi}} \exp\left(\frac{-(D_i - M_i)^2}{2\sigma_\varepsilon^2}\right), \tag{4}$$

where $M_i$ is the model output given the parameter set $\Theta$. Assuming independent errors, the likelihood of the entire dataset is simply the product of likelihoods of all individual points.

$$\begin{aligned} p(D|\Theta) &= p(D_1, D_2, ..., D_n|\Theta) \\ &= p(D_1|\Theta)p(D_2|\Theta)...p(D_n|\Theta) \end{aligned} \tag{5}$$

Computing the likelihood requires having generated a sufficient dataset so that the probability of parameter combinations can be adequately determined. For this study 100,000 simulations were performed with uniform random sampling of the parameter set, i.e. the only prior knowledge considered were lower/upper bounds. With the 100,000 datasets, and the surrogate data, the posterior probability of the parameters was accomplished.

# RESULTS

## Parameter Estimation

To compare results between least squares parameter estimation and the Bayesian methods, the 2,500 solutions from the least squares results were plotted on top of the 2-D contour slices of the posterior distribution. This allows for direct comparison of the probability of a least squares solution from the Bayesian perspective. It is noted that the figures presented herein have been focused to show least squares solutions and the most likely Bayesian estimation ($p_{max}$); the entire parameter space is not represented and additional areas of lower probability may exist outside the plotted region. Furthermore, for the results shown ($\sigma_\varepsilon = 0.15$) the fifteen most likely solution sets have a probability range of 0.01 to 0.11. Although seemingly low, a parameter set probability of 0.01 is still among probable solutions. The magnitude of these probabilities is inherently related to the uncertainty in the problem, namely the measurement error, and the fact a time series of data are considered for the parameter estimation task. A more in-depth discussion of the $\sigma_\varepsilon$ influence in the estimation task is provided in section: Sensitivity to $\sigma_\varepsilon$.

The first posterior distribution slice is shown in Fig. 2, and shows that the least squares approach chose solutions near a region of lower probability for $R_1$ and $R_2$. This region is associated with higher values of $R_1$ and lower values of $R_2$. Together with the thermal mass ($C$), $R_1$ and $R_2$ define the external building envelope characteristics. This observed inverse relationship in the posterior is consistent with describing the overall envelope resistance. That is, a decrease in the interior resistance would require an increase in the external resistance to maintain the same total resistance.

Plotting $R_2$ and $R_3$ in Fig. 3 shows the least squares estimates are approximately associated with the 0.01 Bayesian probability contour around the maximum. This region is associated with lower internal envelope resistances ($R2$) and higher convection resistances ($R3$). This inverse relationship could represent larger envelope heat transfer to the interior surface node with decreased conduction heat transfer to the zone air, resulting in similar overall heat transfer.

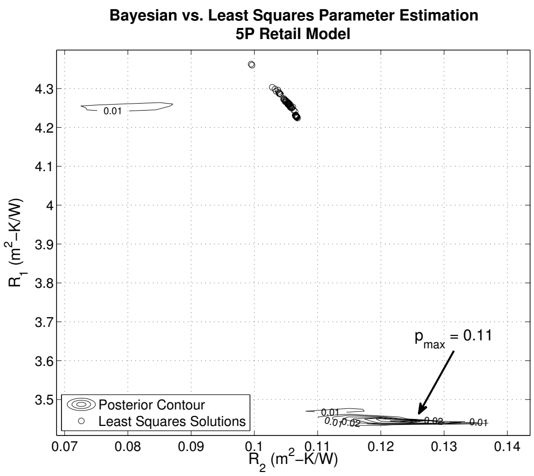


Figure 2: Posterior contour for $R_2$ and $R_1$ with least squares solutions.

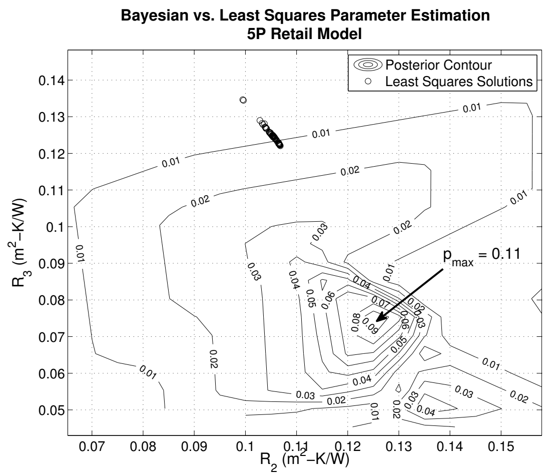


Figure 3: Posterior contour for $R_2$ and $R_3$ with least squares solutions.

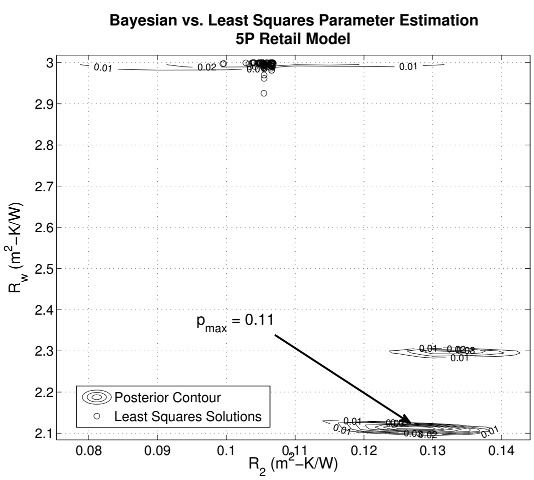


Figure 4: Posterior contour for $R_2$ and $R_w$ with least squares solutions.

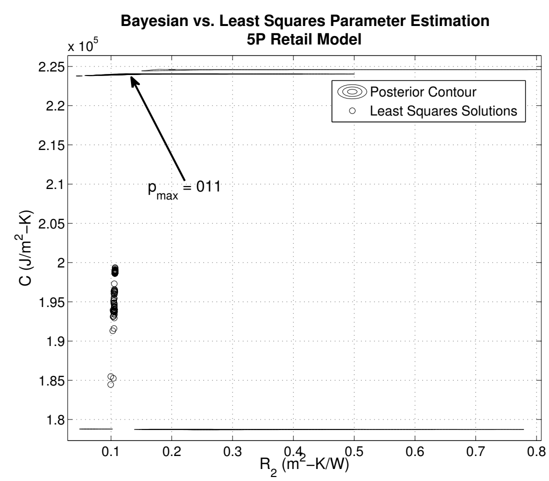


Figure 5: Posterior contour for $R_2$ and $C$ with least squares solutions.

Least squares estimates of $R_w$ are also associated with lower probabilities as shown in Fig. 4. With respect to the most likely Bayesian parameter set, solutions in this region have decreased internal envelope resistances ($R_2$) and increased window resistances ($R_w$). The inverse relationship is again observed where a potential reduction in overall envelope resistance may be accompanied by and increase in window resistance. However, the inverse relationship between these two parameters is not as clearly defined due the overlap of probable regions in the $R_2$ domain, suggesting other parameter interactions as well.

Solutions for the mass element, $C$, were spread between two probable regions shown in Fig. 5. The prior distributions were set to encapsulate a large range of construction possibilities,

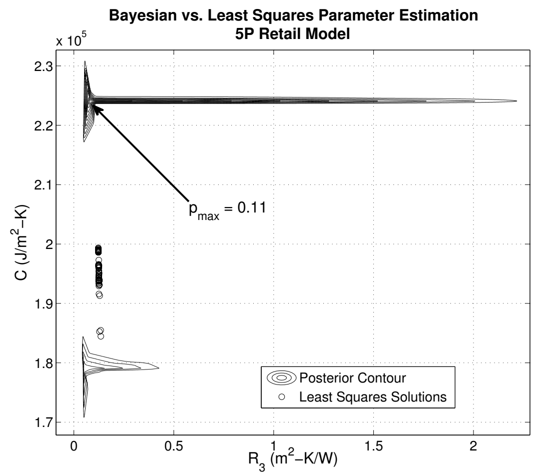


Figure 6: Posterior contour for $R_3$ and $C$ with least squares solutions.

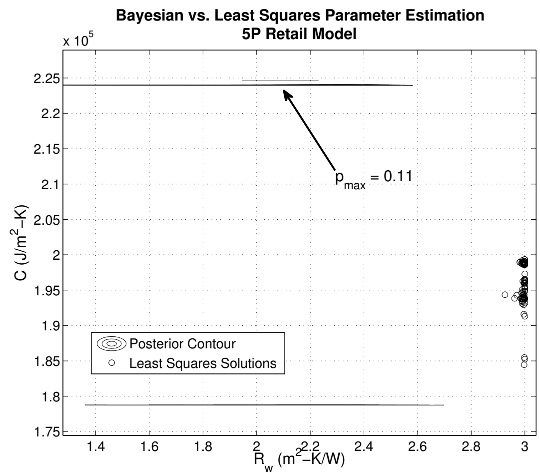


Figure 7: Posterior contour for $R_w$ and $C$ with least squares solutions.

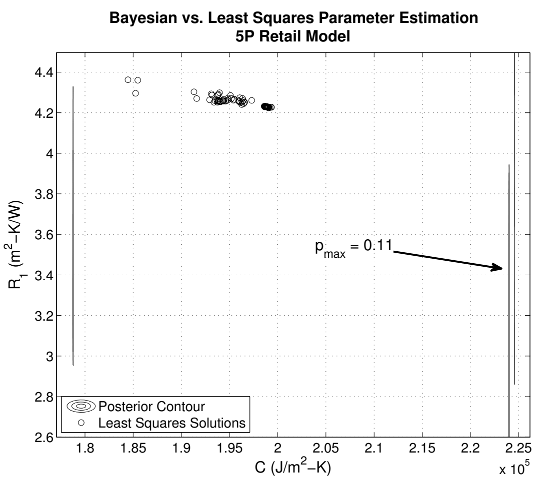


Figure 8: Posterior contour for $C$ and $R_1$ with least squares solutions.

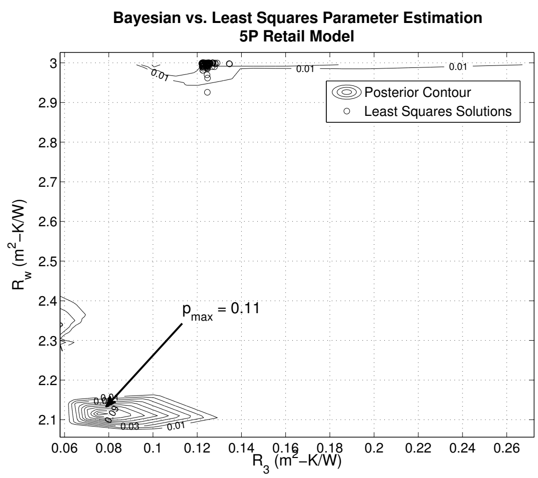


Figure 9: Posterior contour for $R_3$ and $R_w$ with least squares solutions.

however this range is numerically much larger for the $C$ parameter. A further investigation of the results showed that only 8% of the sampled $C$ values were in this range. The range of capacitance between these two regions is approximately equivalent to a concrete wall of thickness ranging from 9.6 to 12 cm (3.78 to 4.72 in.), which represent fairly similar constructions. It is possible the large parameter bounds prohibited adequate sampling to provide high resolution posterior information in this region. The results could potentially be improved by using the initial estimates to update the parameter bounds and narrow the solution space. Similar results are observed in the $R_3C$, $R_wC$, and $R_1C$ posterior slices in Figs. 6, 7, and 8 respectively.

Fig. 9 and Fig. 10 highlight potential direct interactions between the window resistance

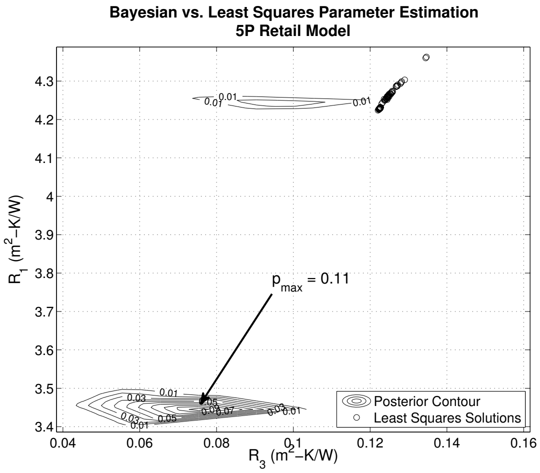


Figure 10: Posterior contour for $R_3$ and $R_1$ with least squares solutions.

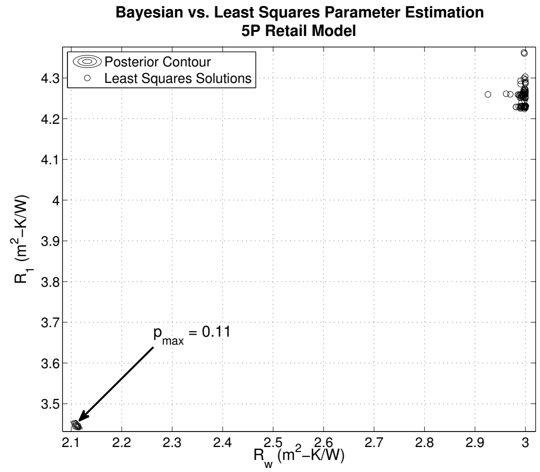


Figure 11: Posterior contour for $R_w$ and $R_1$ with least squares solutions.

($R_w$), external envelope resistance ($R_1$) and the convection resistance ($R_3$). This could represent a scenario where decreased envelope heat transfer produces higher surface node temperatures, requiring additional increase in the convection resistance to prevent excess heat transfer to the zone air.

The largest discrepancy between the two methods was observed in the external envelope resistance ($R_1$) and window resistance ($R_w$) estimates. Fig. 11 shows the least squares solutions do not occupy a region with probability 0.01 or greater. Table 2 highlights the best parameters from the two methods, and in the case of the 2,500 least squares estimations, the median parameter values are reported. Overall the least squares method selects parameters that result in overall higher envelope resistance and increased convection resistance.

## Parameter Performance

The models utilized 21 days of surrogate February heating data, and then simulated for a validation week in March. The heating season was chosen to take advantage of higher building envelope losses to better estimate envelope parameters. Both parameter sets were able to forecast the heating loads and zone temperatures as shown in Fig. 12. The least squares method produced slightly lower error metrics with respect to zone sensible load forecasts, however the temperature response is virtually identical (Table 1). However, it should be noted that from the Bayesian perspective distance metrics are meaningless and every inference is phrased in terms of probability. The majority of parameters relate the zone connection to the ambient environment. The fact that multiple parameter combinations exist that perform similarly may suggest the model is more sensitive to internal gains rather than ambient temperatures, a typical characteristic of commercial buildings; for the results presented, the reduced order model internal gain inputs were mapped directly from EnergyPlus outputs.

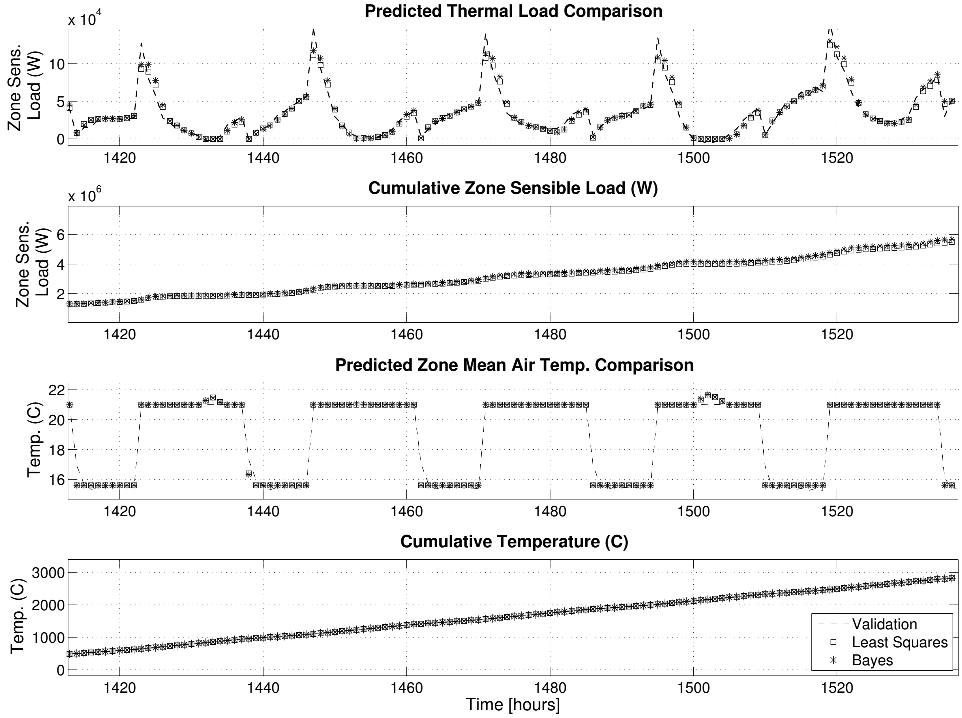


Figure 12: Performance comparison of Bayesian and least squares estimates.

Table 1: Performance Summary Metrics

| | | RMSE | MBE | Cum. % Err. |
|---|---|---|---|---|
| Load | Bayes | 10,692 | 1,802 | 4.491% |
| | NLSQ | 10,250 | 347 | 0.869% |
| Temp | Bayes | 0.299 | 0.0367 | 0.195% |
| | NLSQ | 0.297 | 0.0360 | 0.191% |

Table 2: Retail Model Parameter Estimates

| | R1 | R2 | R3 | Rw | C |
|---|---|---|---|---|---|
| Bayes | 3.445 | 0.128 | 0.075 | 2.11 | 224,015 |
| NLSQ | 4.231 | 0.107 | 0.123 | 2.99 | 198,743 |
| Units | $m^2$-K/W | $m^2$-K/W | $m^2$-K/W | $m^2$-K/W | J/$m^2$-K |

### Sensitivity to $\sigma_\varepsilon$

It was previously noted that the posterior distribution can be sensitive to the measurement error standard deviation ($\sigma_\varepsilon$). For the results provided, $\sigma_\varepsilon$ (Eq. 4) was assumed to be 0.15. This was somewhat arbitrarily chosen through repeated calculation of the posterior with various values of $\sigma_\varepsilon$, but is entirely consistent with high-quality temperature measurement error. If the measurement error is assumed too large all parameter combinations are similarly likely; too small and no parameters are likely, resulting in a meaningless posterior distribution. An error standard deviation of 0.15 was found to clearly distinguish the best parameters while still providing useful information about other parameter combinations and potential interactions. Table 3 shows how the maximum posterior probability changes with $\sigma_\varepsilon$. If $\sigma_\varepsilon$ is approximately less than 0.1, all parameter combinations have zero probability. However, as $\sigma_\varepsilon$ ranges from 0.1 - 0.9 the probability of the best estimate ranges from 0.58 to 0.00001. Despite the range in probabilities, all posteriors give approximately the same best parameter estimates. The difference resides in the information that is conveyed about additional parameter sets. Furthermore, it is reasonable to assume a low measurement error standard deviation (e.g. 0.1 - 0.2) since surrogate measured data was generated through simulation.

## CONCLUSIONS

Overall, the least squares approach produced parameters that were probable from a Bayesian perspective. Bayesian parameter estimation was able to provide additional insight into the estimation task and build confidence in the best parameter set. Bayesian estimation also provides inherent means of incorporating measurement error, which may prove to be more beneficial when dealing with real measured building data and its associated uncertainty.

## FUTURE RESEARCH

Future research seeks to extend the Bayesian methods presented in this paper to n-dimensional time series. That is, the ability to deal with not only surrogate sensible zone loads but temperatures, relative humidities, electrical demands, etc., measured through the BAS and common to modern buildings. Furthermore, the Bayesian approach applies to abstraction of the model itself: 1) the "appropriate reduced order" of the building model, phrased in terms of $p(Model|data)$, and 2) fault diagnostics methods, phrased in terms of $p(Fault|data)$. Any such model-based approach in buildings must inevitably deal with a large degree of uncertainty due to minimal number of measurement points and energy concerns being driven by stochastic weather and occupancy patterns. Uncertainty is escalated in low-energy buildings due to reliance on ambient conditions for natural ventilation, daylighting, and photovoltaic power generation; in the smart grid context a building's (or a portfolio of buildings) electrical demand profile is of great interest. Thus, current research exercises Bayesian probability theory, within a model-based framework and while harnessing measured data, to make inferences of energy and cost concern.

Table 3: Posterior Maximum $\sigma_\varepsilon$ Sensitivity

| $\sigma_\varepsilon$ | p | $\sigma_\varepsilon$ | p | $\sigma_\varepsilon$ | p | $\sigma_\varepsilon$ | p |
|---|---|---|---|---|---|---|---|
| 0.05 | - | 0.1 | 0.57504 | 0.15 | 0.10917 | 0.2 | 0.00314 |
| 0.06 | - | 0.11 | 0.45613 | 0.16 | 0.05170 | 0.3 | 0.00014 |
| 0.07 | - | 0.12 | 0.35964 | 0.17 | 0.02334 | 0.5 | 0.00003 |
| 0.08 | - | 0.13 | 0.27694 | 0.18 | 0.01105 | 0.7 | 0.00002 |
| 0.09 | - | 0.14 | 0.19252 | 0.19 | 0.00566 | 0.9 | 0.00001 |

## ACKNOWLEDGMENT

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# COMPARISON OF SHADING CONTROL MODES ON OFFICES SPACE ENERGY PERFORMANCE

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## ABSTRACT

Interior roller shades are widely used in office buildings to control solar heat gain and glare. Automated operation can result in energy savings depending on the control strategy used. This paper investigates the impact of shading control modes on office space energy performance using year-round transient integrated thermal and lighting simulation.

For office spaces, the most important function of interior roller shades is to block direct sunlight so that the occupants are not disturbed by glare. In this paper, four shading control modes, all of which are developed to settle glare problems, are analyzed and compared. In the first control mode, the roller shades automatically close completely when direct solar radiation is incident on the façade. The second shading control algorithm improved the first by closing shades when daylight illuminance transmitted through glazing exceeds a certain value, which can be determined by real-time full scale measurements or simulation. In the third control mode, the shades do not close completely but move to a position to just prevent direct sunlight from projecting on the work plane surface at pre-defined distances from the facade. When daylight illuminance is extremely low/high, the shades completely open/close respectively. These extreme values for daylight illuminance can also be obtained from experiments or simulation. In the fourth control mode, thermal considerations are included: on the premise of no glare, the shades close completely when the outdoor temperature is higher than a pre-defined value (in cooling season) and transmitted solar heat gains through the glazing are much higher than the respective value if the shades were closed.

After developing the shading control modes, a transient lighting and thermal simulation model, validated by experimental measurements, was used to estimate the annual lighting, heating and cooling demand for a typical private office space with different window size and shading properties. The results show the effects of interior roller shade controls on office space daylight performance and energy consumption.

**Keywords:** shading control, visual comfort, daylight autonomy, energy demand

## 1. INTRODUCTION

Interior roller shades are widely used in office spaces to control solar heat gain and visual comfort. Their properties have significant impact on space daylight availability, and hence on energy demand for space lighting, heating and cooling. Commonly, shading devices are assumed to stay at a fixed position in annual evaluation of energy consumption. However, researches on automated operation of shading devices have shown great potentials in energy saving (Moeseke et al., 2007; Tzempelikos and Athienitis, 2007; Nielsen et al., 2011; Shen and Tzempelikos, 2012a). Various shading control algorithms have been used in existing literature, for example, some studies use transmitted/incident beam solar radiation (Lee and Selkowitz, 1995; Reinhart, 2004; Shen and Tzempelikos, 2012a) as criteria to operate shading devices, some others operate shades based on incident total irradiation or internal temperatures (Moeseke et al., 2007; Newsham, 1994; Georg et al., 1997), and different shading control strategies may achieve diverse performance (Palmero-Marrero and Oliveira, 2010). Nowadays, the advanced whole building simulation programs including EnergyPlus (EnergyPlus, 2007) have already integrated deterministic shading control patterns based on work plane illuminance, glare indices, solar radiation, temperature and thermal demands, although the shading positions are only limited to fully on and fully off conditions.

Generally, in existing literatures the same parameter threshold is applied to all space design alternatives (space dimension, window size, space orientation, shading properties). For example, Vartiainen (2001) assumed that the shading device is lowered completely when direct sunlight is present; and Selkowitz (1995) suggested that the shades should close when the transmitted direct solar radiation is higher than 94.5 $W/m^2$, without differentiating between different space dimensions, window size or shading properties. In addition, the sophisticated characterizations of glazing and shading system require more careful decisions on control parameters and control thresholds. In the sense of glare control, it may as well be more reasonable to use illuminance rather than solar radiation as a threshold basis in automated shade operation.

This paper investigates the impact of shading control modes on office space energy performance using year-round transient thermal and lighting integrated simulation (Shen and Tzempelikos, 2012b). For office spaces, the most important function of interior roller shades is to block direct sunlight so that the occupants are not disturbed by glare. So four shading control algorithms are developed to maximize daylight utilization, minimize energy consumption and reduce the risk of visual discomfort according to different shading properties. Space lighting, heating and cooling demand and source energy consumption are compared between different control algorithms. The time fraction when work plane illuminance exceeds the recommended value during office hours is also investigated.

## 2. DEVELOPMENT OF SHADING CONTROL ALGORITHMS

The development of four types of shading control algorithms are described in detail in the following sections taking a typical private office space as an example.

### 2.1 Shading Control Algorithm I

The first shading control algorithm is simply the same as used in existing literature. The interior roller shades automatically close completely (Figure 1 (a)) when incident beam radiation on the façade is present (in our case we use a small threshold of 20 $W/m^2$) during office hours (9am-5pm), and they are kept closed during non-office hours.

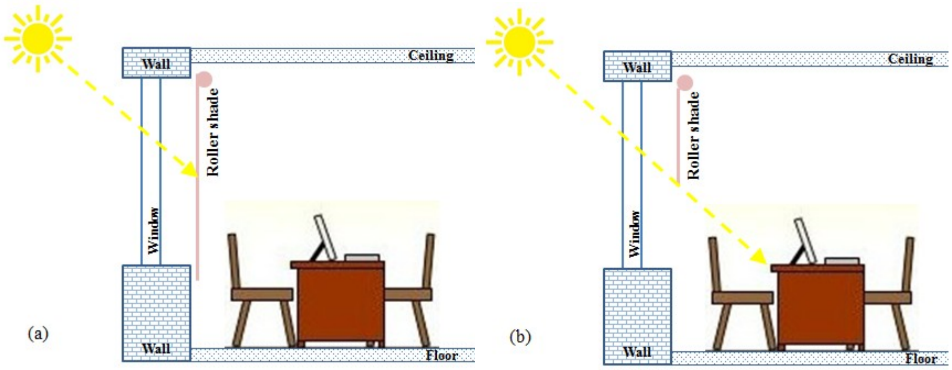


**Figure 1: Schematic view of shade position for different shading control algorithms (a) shade close completely (b) shade close to the position just avoid direct sunlight falling on work plane.**

### 2.2 Shading Control Algorithm II

Recently, more advanced glazing products have gained increasing popularity and gradually replaced the traditional single- and double-glazed window in commercial buildings. One of the several important characteristics of these advanced glazing products is that they usually have beneficial spectral properties (high visible transmittance, low solar transmittance). Therefore, from the viewpoint of glare control, shading devices are better to be controlled based on transmitted illuminance rather than solar radiation. For the second shading control algorithm, the interior roller shades automatically close (Figure 1 (a)) when transmitted illuminance exceeds a certain value, which is defined by measurement or simulation and varies according to the studied space dimension and window size. Figure 2 presents full-scale measured results in a private office space with the variation of measured sensor point illuminance on the work plane as a function of transmitted illuminance through glazing for the case of open shades. For office spaces, the work plane illuminance requirement is 500 lux and is usually preferred to be below 2000 lux to avoid visual discomfort (Dubois, 2003; Nabil and Mardaljevic 2006). So the value of transmitted illuminance corresponding to maximum sensor point illuminance of 2000 lux is the threshold to close shades for this control algorithm (around 5000 lux for the shown condition). Of course, different space dimension and window size require different thresholds which could be determined in similar ways.

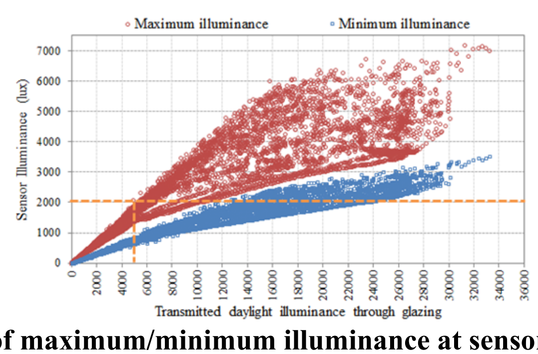


**Figure 2: Variation of maximum/minimum illuminance at sensor points as function of transmitted illuminance through glazing for open shade condition to determine shade close threshold.**

### 2.3 Shading Control Algorithm III

The second control algorithm has the advantage of using a threshold varying with studied space dimension and window size to achieve the recommended work plane illuminance. But it still has limited shade positions (fully open and fully closed). Sometimes the shade may not need necessarily to close completely to avoid visual discomfort and this can lead to waste of beneficial daylight. So in the third shading control algorithm, the interior roller shades close automatically to a position that just prevents direct sunlight from falling on work plane assuming a certain distance between a seated person and the façade (Figure 1 (b)). By doing this, the occupants also get more view to the outside. Except for changing the shade position depending on the solar angles, there are also two thresholds associated with sky conditions in this control algorithm. The lower threshold is the same as in the second shading control algorithm. It is used to open the shades completely when transmitted illuminance through glazing is below the lower threshold to maximize daylight utilization. The upper threshold is determined in a similar way: under closed shade conditions, the transmitted illuminance through the glazing -corresponding to the minimum sensor point illuminance of 500 lux- is the threshold to close the shades completely in order to avoid overheating and excessive daylight.

### 2.4 Shading Control Algorithm IV

In the third control algorithm, shading properties, space dimension and window size are all considered in shading operation. It has advantages in terms of maximizing daylight utilization, but depending on weather conditions, it may also create overheating problems, especially during the summer time. Therefore, one improvement is made in the fourth control method to reduce solar heat gains in the summer: when the outdoor air temperature exceeds a predefined (pre-calculated) value and transmitted solar gain through the glazing is much higher than the respective value with closed shades, then the shades close completely. The temperature threshold can be defined as the cooling set point or slightly higher to guarantee that the space is in cooling mode; and the solar gain difference threshold can be defined as equal to the lighting heat gain when the lamps are fully on. By doing this, the shading control method utilizes maximum daylight without allowing excessive solar gains.

## 3. COMPARISON OF DIFFERENT SHADING CONTROL ALGORITHMS IN A CASE STUDY

The four developed shading control algorithms were applied for a typical private office space located in Philadelphia. Weather data information for Philadelphia were obtained from TMY3 weather data (NREL, 2008) and the Perez model (Perez et al., 1990) was used for prediction of diffuse solar radiation and incident direct and diffuse illuminance on the facade.

The office has one exterior façade with one window facing south. Window frame accounts for 10% of the total window area with a U value of 6.42 $W/m^2 \cdot K$. The transparent part of window is a double-clear glazing (visible transmittance: 0.786, solar transmittance: 0.607 at normal incidence, U-value: 2.689 $W/m^2 \cdot K$). Equipped interior roller shades have a front side absorptance of 30% and a back side absorptance of 70%, which is commonly used in office spaces. The space dimensions are 4m × 4m × 3m high. The interior surface reflectances of the floor, ceiling and walls are 45%, 80% and 50% respectively. The exterior surface absorptance of the external façade is 60%. Occupant density in the space is 0.11 p/m$^2$ and sensible heat gain from each occupant is 76W. Load factor of the office space is 5.4 W/m$^2$ during office hours (ASHRAE, 2009). The lighting system in the space is continuously dimmable to compensate daylighting illuminance so as to reach the illuminance requirement of 500 lux on the work plane (0.8 m above floor). The lighting system has a power density of 10 W/m$^2$ with 30% of the released heat convected directly to the air (ASHRAE, 2009). The other 70% of the heat released by lights goes to all surfaces as internal radiative heat gains according to their respective area-absorptance weights. Heating and cooling are always available throughout the year. The heating set point during office hours is 22 °C and 18 °C otherwise. The cooling set point during office hours is 24 °C and 26 °C otherwise. The heating system consumes natural gas with an overall system efficiency of 80% and the cooling system consumes electricity with an average COP of 3.5. These values are typical and were used to convert thermal loads to source energy use (source-site ratios are 3.34 for electricity and 1.047 for natural gas). Three window sizes (window-to-wall ratio (wwr): 20%, 40%, 60%) and shade transmittances (τ: 5%, 10%, 15%) are investigated.

Daylighting and energy performances are both compared among different shading control algorithms. Evaluated performance metrics include daylight autonomy, time ratio when work plane illuminance exceeds the recommend value, annual lighting, heating and cooling demand per unit floor area and annual source energy consumption per unit floor area.

### 3.1 Shading Control Thresholds

As described in section 2, except for the first shading control algorithm, all other controls require the determination of the thresholds to close or open the shades. The methods how to determine these thresholds according to varying space conditions are also discussed in section 2. Table 1 lists the thresholds used in this case study for all studied shading control algorithms.

**Table 1: Shading control thresholds used in case study**

| Control parameter | | SC-I | SC-II | SC-III | SC-IV |
|---|---|---|---|---|---|
| wwr | $\tau_{shade}$ | Incident solar radiation on facade | Transmitted illuminance through glazing | Sun position & sky condition | Sun position & sky condition & temperature & solar radiation |
| 20% | 5% | | 15000 lux | 15000/NA lux | 15000/NA lux & 26 °C & $A_g \cdot (I_{trg}-I_{trsh}) > E_{light}$ |
| | 10% | | | 15000/80000 lux | 15000/80000 lux & 26 °C & $A_g \cdot (I_{trg}-I_{trsh}) > E_{light}$ |
| | 15% | | | 15000/68000 lux | 15000/68000 lux & 26 °C & $A_g \cdot (I_{trg}-I_{trsh}) > E_{light}$ |
| 40% | 5% | 20 W/m$^2$ | 9000 lux | 9000/80000 lux | 9000/80000 lux & 26 °C & $A_g \cdot (I_{trg}-I_{trsh}) > E_{light}$ |
| | 10% | | | 9000/45000 lux | 9000/45000 lux & 26 °C & $A_g \cdot (I_{trg}-I_{trsh}) > E_{light}$ |
| | 15% | | | 9000/30000 lux | 9000/30000 lux & 26 °C & $A_g \cdot (I_{trg}-I_{trsh}) > E_{light}$ |
| 60% | 5% | | 7500 lux | 7500/65000 lux | 7500/65000 lux & 26 °C & $A_g \cdot (I_{trg}-I_{trsh}) > E_{light}$ |
| | 10% | | | 7500/30000 lux | 7500/30000 lux & 26 °C & $A_g \cdot (I_{trg}-I_{trsh}) > E_{light}$ |
| | 15% | | | 7500/22000 lux | 7500/22000 lux & 26 °C & $A_g \cdot (I_{trg}-I_{trsh}) > E_{light}$ |

* $A_g$ is the area of the open glass part of the window, m$^2$; $I_{trg}$ is transmitted solar radiation through glazing, W/m$^2$; $I_{trsh}$ is transmitted solar radiation through glazing and shading system, W/m$^2$; $E_{light}$ is lighting heat gain when the lamps are fully on, W.

As can be seen in Table 1, shading control algorithm I ignores the studied space condition in terms of space dimension, window size and shading properties. Shading control algorithm II has changing thresholds for different window size, but still ignores the impact of shading properties. For the last two shading control algorithms, the effects of space dimension, window size and shading properties are all considered in their developments. Shading control algorithm IV is based on shading control algorithm III with one improvement regarding solar gains during the cooling period.

### 3.2 Shading Operation and Outdoor View

In all the four shading control algorithms, the interior roller shades are kept closed during non-office hours for privacy purposes. The shading schedules during working hours throughout the year can be expressed as the percentage of time during which shades remain open (Figure 3).

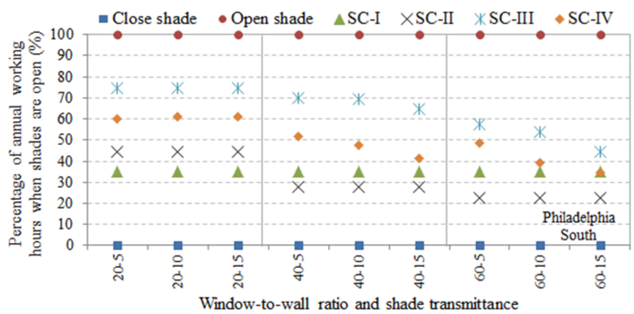


**Figure 3: Percentage of annual time (working hours) during which automated shades remain open for different shading control algorithms.**

In Figure 3, the shading schedules for open shade and close shade conditions are also shown as two extreme shading control methods for comparison. Figure 4 shows that for control algorithm I, all cases have the same shading schedule. This is apparent since all cases use the same threshold to operate shades. For the second shading control algorithm, shading schedule changes with the variation of window size. For the third and fourth shading control algorithms, shading schedules decrease with the increase of window size and shading transmittance, although shading properties in fact have very small impact on shading schedule for small window sizes. Generally, the third shading control algorithm has higher shading open time than other shading control algorithms, followed by the fourth shading control mode. For small window sizes, the second shading control algorithm has higher open times than the first shading control, while at larger window sizes the first shading control algorithm performs better. For the third shading control algorithm, the smaller upper threshold at higher shade transmittance results in lower shade open time, which is also one of the reasons for the results with the fourth shading control mode. Another reason causing lower shade open time at higher shade transmittance for the fourth shading control is that the difference between transmitted solar heat through the glazing the chance of the shade being employed on that part becomes smaller when shade transmittance increases, which further results in lower shading open time. This also explains the lower open time of the fourth shading control algorithm compared to the third control mode.

### 3.3 Daylighting Performance

Figure 4 shows the variation of daylight autonomy for all shading control algorithms.

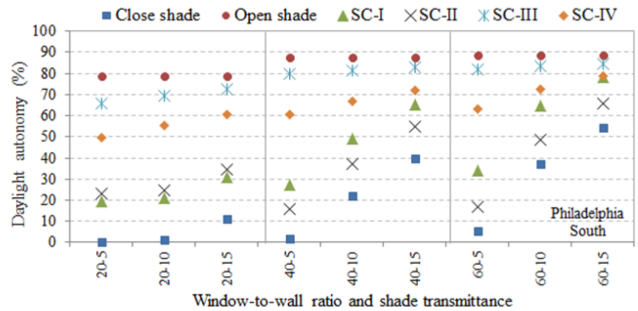


**Figure 4: Daylight autonomy for all studied shading control algorithms**

Generally, the variation of daylight autonomy follows the trends of shade open time comparing different shading control algorithms. However, for each shading control algorithms, daylight autonomy increases with the increase of window size and shade transmittance. Of course, higher daylight autonomy does not mean better daylight performance. The work plane illuminance should also be investigated in terms of preventing high values to avoid glare. Figure 5 shows the time percentage during working hours when work plan illuminance is higher than the recommended 2000 lux threshold.

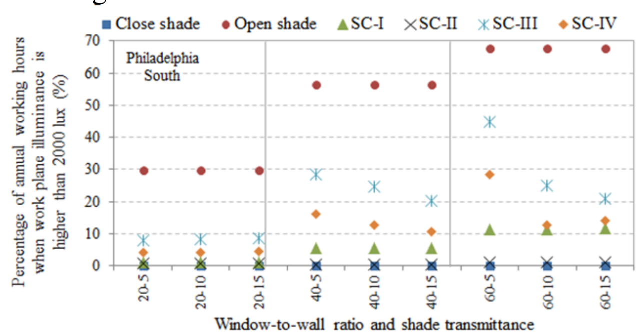


**Figure 5: Percentage of annual time (working hours) during which work plane illuminance exceeds 2000 lux for different shading control algorithms.**

The graph indicates that shading control algorithm III and IV have higher probability of visual discomfort for large window sizes, and the probability increases with the increase of window size and decreases with the increase of shade transmittance. For smaller window sizes (wwr: 20%), all the four developed shading control algorithms show acceptable visual discomfort probability. For the first shading control algorithm, the risk of glare increases with the increase of window size. However, when transmitted illuminance is used as shading control criteria to replace incident solar radiation, the glare risk is greatly improved.

### 3.4 Lighting, Heating and Cooling Demand

Figures 6-8 show the results of space lighting, heating and cooling demand for all shading control algorithms.

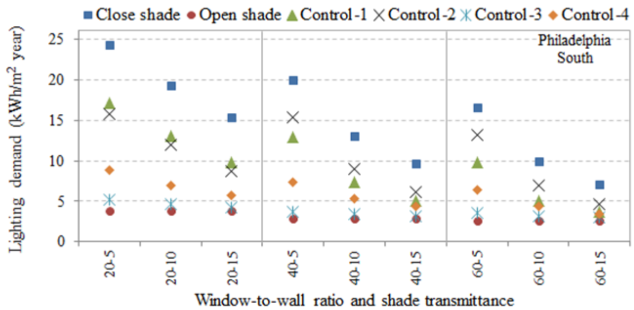


**Figure 6: Annual lighting demand for all studied shading control algorithms**

Overall, the third shading control algorithm results in minimum lighting demand because of its longest shade open time (Figure 3) for all cases. The fourth shading control algorithm results in slightly higher lighting demand for high shade transmittance values. For small window sizes, the first shading control algorithm requires slightly higher lighting demand when compared with the second shading control, but for large window size, they just show the opposite trend in lighting demand. The differences in lighting demand between the four studied shading control algorithms are larger at small window sizes and low shade transmittance values. For high wwr and high shade transmittance, the four shading control algorithms result in closer values.

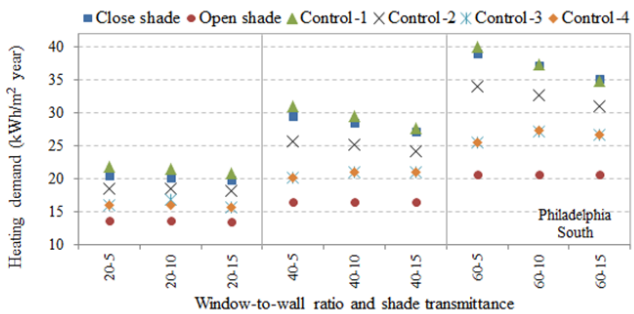


**Figure 7: Annual heating demands for all studied shading control algorithms**

For annual heating demand, the differences between the four studied shading control algorithms are larger at high wwr and shade transmittance. The first shading control algorithm results in highest heating demand: for some cases even higher than the case with fully closed shade throughout the year. This indicates that the presence of interior roller shades can increase the effective thermal resistance of the glazing-shading system (for particular configurations) which results in less heating requirement at cold and dark weather conditions during office hours. For small window sizes, the shading transmittance has almost no impact on heating demand. For large windows, the first and second shading control algorithms result in decreasing heating demand as the shading transmittance increases. The third and fourth shading control algorithms result in the same heating demand which is explained by the same shading operation during the heating period. For these two shading control algorithms, heating demand naturally increases with shade transmittance.

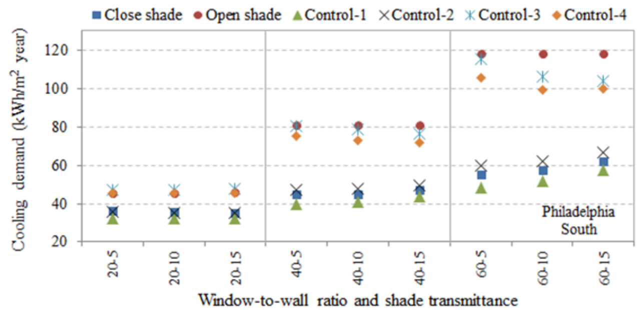


**Figure 8: Annual cooling demands for all studied shading control algorithms**

Figure 8 shows more complex variations of cooling demand as a function of window relative size and shading transmittance. The third shading control algorithm results in the highest cooling demand, sometimes even higher compared to the case with fully open shades for small windows. This phenomenon indicates the sophisticated integration required between daylight benefits and thermal requirements which are interrelated through internal lighting heat gains. The third and fourth shading control algorithms result in similar cooling demands. This result may seem strange since the improvement of shading control IV to shading control III is to avoid excessive daylight and heat gain hence to reduce cooling load. However, this may be explained by the fact that a potential amount of cooling demand happens in winter when the outdoor air temperature is below the defined shade close threshold in this case study. A further improvement may be to control the shade based on the HVAC system working mode. For example, in shading control algorithm IV, it might be more reasonable to use thermal load values to decide if it is in cooling mode instead of the outdoor air temperature. This work is planned as the next step of this study.

## 4. DISCUSSION AND CONCLUSION

Four shading control algorithms were developed in this paper. Shading control algorithm I was a simple method that was generally used in existing literature for dynamic shading study: interior roller shades close automatically to block direct sunlight completely (20 $W/m^2$ is used in this paper to avoid too frequent shade operation). The second control algorithm improved shading control algorithm I by using the transmitted illuminance through glazing as the control criterion instead of incident solar radiation on facade. The third shading control algorithm closes the shades to a position so as to avoid direct sunlight falling on work plane to maximize daylight utilization, based on which the fourth shading control algorithm made further improvement to reduce excessive daylight and solar heat gains. The thresholds for the last three shading control algorithms can be obtained by measurements or simulation, considering the variety of space dimensions, window size and shading properties.

The second shading control algorithm shows better performance than the first shading control algorithm in terms of keeping work plane illuminance within the recommended range. It also has varying thresholds in shade operation according to different space dimension and window size. But the two algorithms have the same limitation of having two shade positions (fully closed or fully open), which limits the outdoor view and reduces utilization of natural light.

In the last two shading control algorithms, the shade positions are changing with the solar angles and the sky condition. In general, the third shading control algorithm results in the longest shading open time during office hours, and hence highest daylight autonomy, minimum annual lighting and heating demand are observed. But it also results in higher visual discomfort probability and increase in annual cooling demand. The fourth shading control algorithm is developed to reduce the cooling load based on the third shading control logic. However, the results show close cooling demand values for the two control algorithms. One reasonable improvement is to use thermal load values to determine if the space is in cooling mode instead of using outdoor air temperatures, which will further reduce overheating in winter time.

This study presented a comparison of daylight performance and thermal load between the four developed shading control algorithms. However, the results only reveal the comparison for a south-facing private office space located in Philadelphia. For another location with different weather condition or spaces facing other orientations, the results may change significantly. A more comprehensive and systematic study is required to determine which shading control algorithm is the most beneficial one for different locations and space configurations. The impact of weather conditions, space orientation and glazing properties are the ongoing works of the study.

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# MODELING AND PREDICTIVE CONTROL OF MIXED-MODE BUILDINGS WITH MATLAB/GENOPT

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## ABSTRACT

The paper presents a transient multi-zone thermal model and anticipatory control strategies for a building with mixed-mode cooling. The model is based on the thermal network representation with advective heat transfer for modeling the heat exchange due to air flow between thermal zones. It is developed in Matlab, which is coupled with GenOpt as an optimizer. The paper presents results of simulations which model the performance of night cooling using "offline" predictive control strategies. Results show that the cooling load can be efficiently reduced by following the sequences based on anticipatory control techniques. The impact of building design parameters on the development of model-predictive control (MPC) strategies and the decisions made by the MPC controller are also discussed.

**Keywords:** GenOpt, Mixed-mode cooling, Model predictive control, Natural Ventilation, Particle swarm optimization, Thermal mass.

## 1. INTRODUCTION

Mixed-mode refers to a hybrid approach for space conditioning that uses a combination of natural ventilation from operable windows (either manually or automatically controlled) or other inlet vents, and mechanical systems that provide air distribution and some form of cooling (Brager et al., 2007). Night cooling is an essential feature of mixed-mode buildings as it can significantly reduce the cooling load on the following day but its performance is affected by (a) design parameters, such as building construction, glazing ratio, façade orientation, and shading position; (b) control parameters including ventilation flow rate, ventilation time and indoor air temperature set point; and (c) disturbance parameters, i.e. weather conditions, internal heat gains, and infiltration (Braun, 1990; Spindler and Norford, 2009a, 2009b; Kolokotroni and Aronis, 1999). Therefore, this hybrid cooling system requires an integrated design approach including façade optimization for solar heat gains, exposed thermal mass made possible by the structural design and interior space planning, together with improved understanding of complex heat and fluid flow phenomena and coordinated intelligent controls to enable high performance. For buildings with pre-determined design parameters, the performance can only be improved by applying better control strategies.

Existing techniques for mixed-mode buildings are heuristic, i.e. based on fixed schedules that are not optimized for the particular building design or climate and may lead to increased operating costs or occupant discomfort (de Dear and Brager, 1998). These problems can be avoided by employing model predictive control strategies (MPC) for the operation of night cooling (Spindler and Norford, 2009a, 2009b; May-Ostendorp et al., 2011). However, the efficiency of MPC strategies relies on the accuracy of the prediction model and the decisions made by the optimization algorithm. Furthermore, real-time or "online" predictive control has an additional requirement of computational speed. May-Ostendorp et al. (2011) combined an optimization toolbox in Matlab with EnergyPlus to generate optimal window opening schedules for a mixed-mode building. The optimal results were used to create a generalized linear model to extract near-optimal heuristics. Coffey (2011) developed an "online" control methodology by using lookup tables which were established by using TRNSYS as building simulation model and GenOpt (Wetter, 2011) as optimization module. Both studies applied a detailed prediction model that would lead to a computationally expensive optimal decision process that would limit the "online" MPC implementation. One alternative way to implement "online" predictive controls is by using simplified or reduced-order building simulation models. Braun (2002) developed a "gray-box" modeling approach that uses a transfer function with parameters identified using a nonlinear regression algorithm. Results from a case study building indicated that the model could accurately predict transient heating and cooling requirements. Candanedo (2011) used the system identification toolbox in Matlab and training data from EnergyPlus to create transfer functions in frequency domain. The simplified building model was applied to develop MPC strategies for the operation of a radiant floor heating system and the position of roller blinds in a room with high solar gains. However, the nonlinearity caused by natural ventilation systems is an additional complexity for developing reduced-order modes for buildings with mixed-mode cooling. Spindler (2009) presented a flexible system-identification framework for linear thermal models for a building with mixed-mode cooling and it was proved to be reliable through its implementation on other buildings. Nevertheless, the accuracy of the developed model is subject to the availability of experimental data.

The goal of the present research is to develop "offline" and "on-line" MPC strategies for mixed-mode buildings. This paper presents a transient thermal model, developed in Matlab for a generic section of a multi-zone building with mixed-mode cooling, exposed thermal mass, and high solar heat gains. The building's natural ventilation design includes motorized façade grilles, an atrium and a variable speed exhaust fan. The model has been validated using data from an extensive experimental study (Karava, et al. 2012; Hu and Karava, 2012a) and it is used with GenOpt as the optimizer to develop offline MPC strategies for night cooling. Simulation results are presented for a single day and for six consecutive days to evaluate the potential of MPC in mixed-mode buildings.

## 2. MODEL DESCRIPTION

A transient thermal model was developed in Matlab for a building section (Mouriki, 2009; Karava, et al., 2012) with an atrium connected to six corridors as shown in Figure 1. Each corridor has one exterior façade where the inlet grilles are installed and it acts as long air "duct" for delivery of outside air into the atrium zone. A schematic of the thermal network for the atrium and the corridors is shown in Figures 1 and 2. Due to the corridor's large dimension (30 m long) a significant temperature difference is anticipated in the slab surface, thus, it is divided into 4 sections (Figure 2). The heat transfer by conduction and radiation is calculated using thermal resistance models (Athienitis, 1998). The advective heat transfer associated with air flow, such as the infiltration and air exchange between the corridor and atrium zones, can be computed from:

$$\dot{Q}_{ij}^{adv} = F\dot{m}_{ij}c_p(T_j - T_i) \tag{1}$$

where, F is the upwind operator which is used in order to account for influence from the upwind control volume j to volume i: F=1.0 if the flow is from volume j to i and F=0 otherwise; $\dot{m}_{ij}$ is the mass flow rate of air, $c_p$ is the specific heat of air, $T_i$ and $T_j$ is the air temperature in zone i and j respectively. The study assumes that outdoor air is driven using an exhaust fan and it is transferred into the atrium through corridors when the night

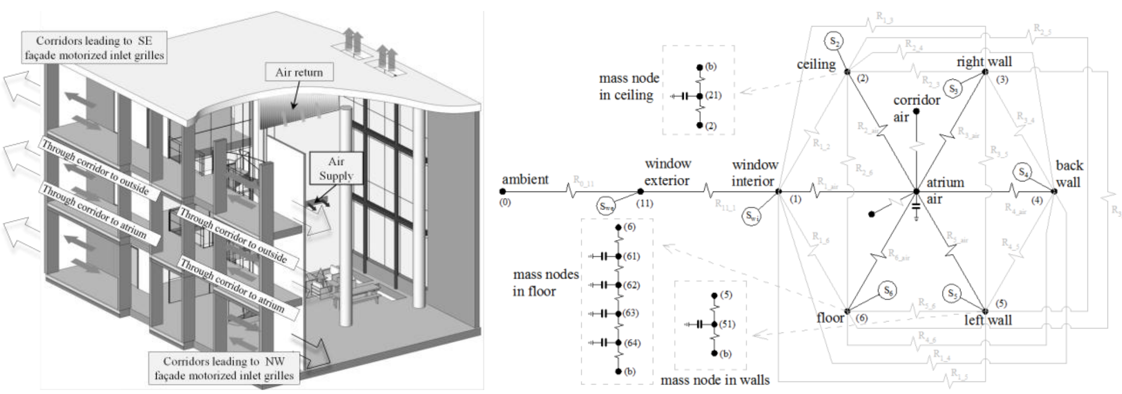



**Figure 1:** Mixed-mode cooling concept (*left*); the thermal network for the atrium (*right*)

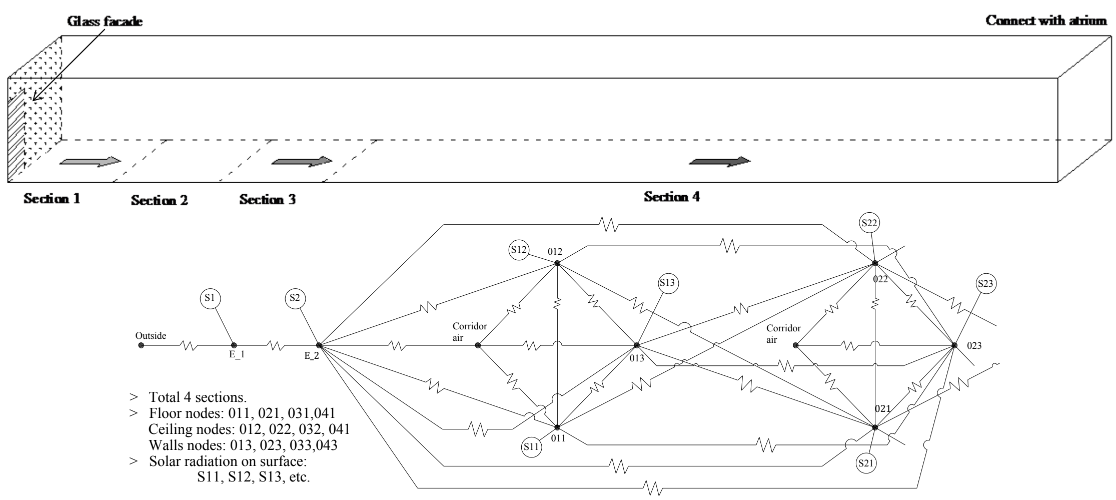



**Figure 2:** Corridor configuration with control volumes (*top*) and thermal network for sections 1 and 2 (*bottom*)

cooling is in operational mode, otherwise, the air exchange between the atrium and corridors is controlled by a secondary re-circulation fan. For the range of relative magnitudes of the Grashof number and squared Reynolds number (based on approaching velocity and corridor length in the stream-wise direction), mixed convective heat transfer is assumed between the corridor slab surfaces and the air nodes. For the range of Reynolds number considered here, the boundary layer on slab surfaces can be assumed to be laminar, thus, the forced convection correlation for a laminar boundary layer over a smooth flat plate is used. The heat transfer between the atrium surfaces and air is by natural convection. The heat transfer coefficients (CHTC) for natural convection are calculated using the correlations in Table A in the Appendix while, the blending function proposed by Neiswanger et al. (1987) is used for mixed convection:

$$h_{mx} = (h_f^{\varepsilon} + h_n^{\varepsilon})^{1/\varepsilon} \tag{2}$$

where, $h_f$ is the CHTC for forced convection and $h_n$ is the CHTC for natural convection. This equation has been used in room heat transfer studies (e.g. Carrilho da Graca, 2003) with ε equal to 3.2. The energy balance of the air node i leads to:

$$A_{wi}h_{wi}(T_{wi} - T_i) + A_{ci}h_{ci}(T_{ci} - T_i) + A_{fi}h_{fi}(T_{fi} - T_i) + FC_i(T_j - T_i) = 0 \tag{3}$$

where, $C_i$ is product of mass flow rate and specific heat, h, T and A is the CHTC, temperature and area of the wall, ceiling and floor surface.

In the present work, the solar radiation is the only heat gain to the zone. TMY3 solar radiation data are used as inputs to the Perez model (Perez et al., 1990). The window (glass façade shown in Figure 1 and 2) is double-glazed and argon-filled with a low-e coating. The window properties (beam and diffuse transmittance and absorptance) were obtained from WINDOW 6 (LBNL, 2011). The model was used to investigate the impact of different parameters on night cooling effectiveness in reducing the cooling load in the atrium on the following day. Results show that the air flow rate has the most pronounced impact on mixed-mode cooling performance followed by the thermal mass and glazing area (Hu and Karava, 2012b). The night cooling effectiveness can be improved with higher thermal mass in the direct gain zone. However, the mass in other zones should be carefully fixed to a specific value as the improper heat release during occupancy hours could increase the cooling load, thereby reducing the effectiveness of night cooling. The thermal properties of the building elements are listed in Appendix (Table B).

## 3. "OFFLINE" MPC FORMULATION

With regards to the use of MPC for building energy management, the sequence for building climate control (e.g. air temperature set-point, night cooling) is formulated at a given point in time for a future planning horizon, based on the prediction of upcoming weather conditions. A framework for MPC implementation in buildings with mixed-mode cooling is illustrated in Figure 3. The framework contains three main components. The first is a dynamic model used for evaluating the cost function which has two sub-components: a detailed model and a reduced-order model.

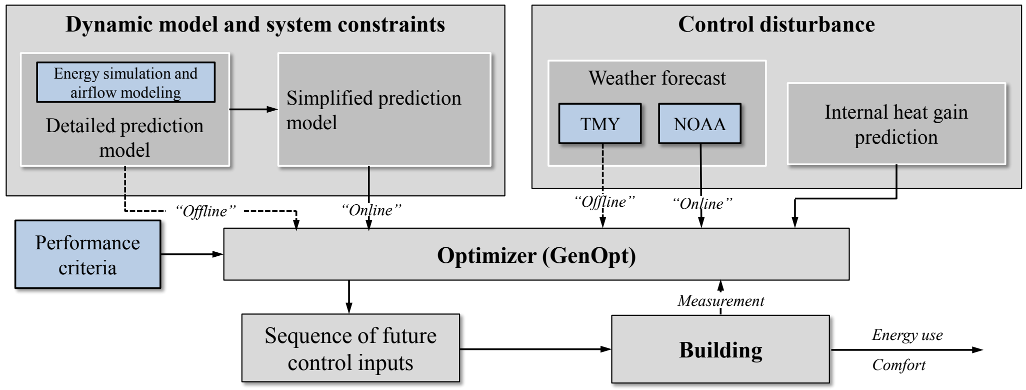



**Figure 3**: Framework of model predictive control for mixed-mode cooling

The detailed model is based on physical principles with a detailed description of the heat and mass transfer processes in the building, while the simplified model is developed from the detailed model by using forcing function to find transfer function models or using the state-space order reduction method to find a reduced-order model. The detailed model can be used for "offline" MPC when the system disturbances during the planning horizon are accurately predicted and thus, optimal control decisions are not required so frequently. Therefore, "offline" MPC is based on the assumption of flawless weather forecast. The TMY weather data are used as "inputs", which is shown in "control disturbance" – the second main component of the control framework. The "online" MPC refers to the predictive control implemented in a building with a real-time weather forecast. Due to the stochastic nature of weather forecast, the "online" MPC requires the control system to frequently update optimal decisions for the planning horizon. Although the frequency of the optimal decision process could be reduced by accepting some uncertainty from the disturbance, e.g., optimal decisions could be made every two hours instead of every hour, the computational time for "online" MPC is still a limiting factor creating the need for reduced-order models. The third main component of the framework is the optimizer which is used for generating a sequence of future control inputs.

The goal of MPC for mixed-mode buildings is to minimize energy use while maintaining the operative temperature within a comfort range by intelligent switching between free and mechanical cooling. In the present study, night cooling is the only mixed-mode feature and the outdoor air is driven into the building by a mechanical fan. The decision space is the ventilation flow rate at night time (20:00-6:00) and the objective is to minimize energy use. The problem can be mathematically formulated as:

$$\text{Minimize: } J(\dot{q}_t) = \alpha \cdot \frac{|Q|}{|Q|_{baseline}} + (1-\alpha) \cdot \frac{\Sigma|T_{ope} - T_{ope\_set}|}{(\Sigma|T_{ope} - T_{ope\_set}|)_{baseline}} \quad (4)$$

Subject to: $\dot{q}_t = \{0, 0.125, 0.25, \ldots, 1.0\}$ $m^3/s$

where, $\dot{q}_t$ is the night ventilation flow rate during the planning horizon and its range is decided based on experimental data. In this case, the planning horizon is the period from 20:00 at night to 6:00 on the following day and it is segmented into 5 blocks of 2 h duration. During each block the optimizer makes one decision on the flow rate. $|Q|$ is the total energy consumption which is the sum of cooling energy and fan energy consumption. $T_{ope}$ is the operative temperature. Both energy use and operative temperature are normalized by their values when night cooling is not operating. α and (1-α) are the weighting factors for energy consumption and thermal comfort respectively. The disturbance control variables are the outdoor temperature and solar radiation. The basic assumptions and limitations of the present study are outlined below:

- The weather forecast is perfectly accurate.
- Latent heat is not considered.

The cost function is not in the form that can allow the use of traditional gradient or pattern search techniques as it can contain many local minima. Therefore, the particle swarm optimization (PSO) (Kennedy and Eberhart, 1995) algorithm is adopted to search the decision space for near-optimal solutions. PSO has already been embedded in GenOpt (Tuhus-Dubrow and Krarti, 2009; Coffey, 2011) – an optimization module for the minimization of a cost function that is evaluated by an external simulation program – which is carefully tuned with improvements for settings of parameters like neighborhood topology, decision space discretization, and seeding.

## 4. RESULTS AND DISCUSSION

The performance of the MPC strategy is demonstrated considering simulations for a single day and multiple days. The corresponding Philadelphia weather conditions are shown in Figure 4(a) and Figure 5(a). A comfort penalty is added by setting the weighting factor to be 0.75 while the desired operative temperature ($T_{ope\_set}$) range is between 23 °C and 26 °C (ASHRAE 2004) for both cases (baseline and MPC). For the specific building and weather conditions, different weighting factors ranging from 0 to 1 were examined and the results indicate that the factors have negligible influence on the optimal decisions made by MPC controller. Figure 4 shows that for the weather conditions considered, the cooling load can be significantly reduced while also reducing the cumulative difference of the operative temperature from the desired range, by using an optimal night ventilation rate. The "offline" MPC strategy is proved to be an efficient way to find potential trade-offs between energy reduction and occupant comfort. Previous studies have shown that building design parameters have a significant impact on night cooling effectiveness (Hu and Karava, 2012b). However, the influences of these parameters on optimal control strategies remain unexplored. The study explores the influence through evaluating the cooling load reduction obtained from

$$Reduction = \frac{Q_{Cooling\_baseline} - Q_{Cooling\_MPC}}{Q_{Cooling\_baseline}} \quad (5)$$

where $Q_{Cooling\_baseline}$ is the cooling load for the baseline case for each parameter and $Q_{Cooling\_MPC}$ is the cooling load with the optimal night cooling control sequence. Table 1 lists the cases with different design parameters and the corresponding night cooling

**Table 1**: Optimal ventilation flow rate sequence

| Cases | Design Parameters | Optimal NV Flow Rate ($m^3/s$) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 20:00 | 22:00 | 24:00 | 02:00 | 04:00 | 06:00 |
| 1 | Atrium floor thickness 0.4 m, 60% glazing without shading (S) | 0.125 | 0.125 | 0.125 | 0.25 | 0.25 | 0 |
| 2 | Atrium floor thickness 0.1 m, 60% glazing without shading (S) | 0 | 0.125 | 0.125 | 0.125 | 0.125 | 0 |
| 3 | Atrium floor thickness 0.05 m, 60% glazing without shading (S) | 0 | 0 | 0.125 | 0.125 | 0.125 | 0 |
| 4 | Atrium floor thickness 0.4 m, 60% glazing with shading (S) | 0 | 0 | 0 | 0.125 | 0 | 0 |
| 5 | Atrium floor thickness 0.4 m, 90% glazing without shading (S) | 0.125 | 0.25 | 0.25 | 0.375 | 0.375 | 0.25 |

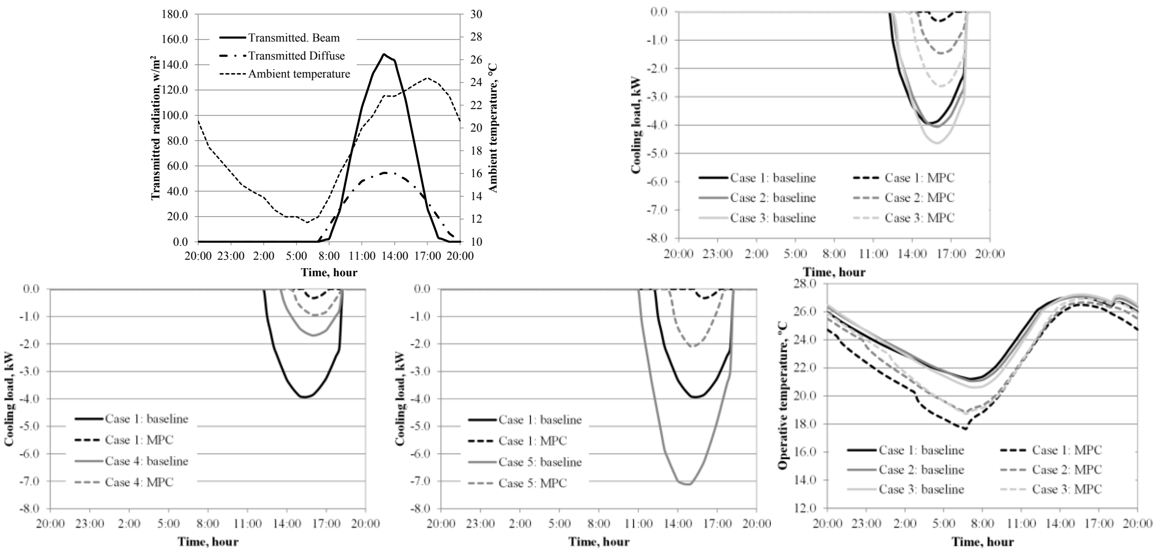
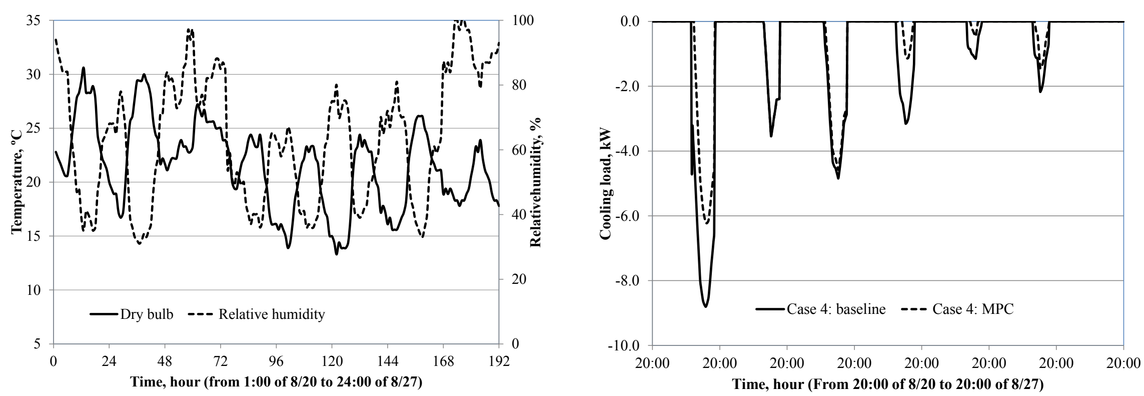



**Figure 4**: Results for "offline" MPC – single day simulation: (a) Outdoor air temperature and solar radiation (*top left*); (b) load with different thermal mass (*top right*); (c) load with different shading position (*bottom left*); (d) load with different glazing area (*bottom center*); (e) operative temperature with different thermal mass (*bottom right*);

control sequences. For example, higher thermal mass stores more heat and therefore, more heat can be moved away with night cooling. The controller generates a control sequence with high ventilation rates and therefore higher cooling load reduction can be achieved compared to the baseline case (where cooling load anticipation is not considered), namely 56%, 77% and 97% for case 1, 2 and 3 respectively (Figure 4b). Solar heat gains are lower for the case with shading control (the transmittance of glazing-plus-shade is reduced to 60% of the value without shade), thus lower night ventilation rate would be required (Figure 4c). For the case with larger glazing area, the higher solar heat gains result in higher ventilation rates compared to other cases. Figure 4(d) indicates that although larger glazing area requires more cooling load, the percentage of cooling load reduction for 60% and 90% glazing area (case 1 and 5) is similar, i.e. 97% and 93% respectively. With regards to the simulation for multiple days, an extra constrain is imposed – there will be no night cooling when the outside relative humidity is higher than 80%. Table 2 shows the optimal ventilation flow rate sequence during a period of six consecutive days for Case 4 with the results showing significant variations, for the same thermal comfort constraints, based on the cooling load anticipation. The corresponding cooling load results shown in Figure 5 demonstrate improved performance compared to the reference case.

**Table 2:** Optimal ventilation flow rate sequence during six consecutive days for case 4

| Date | Optimal NV Flow Rate ($m^3/s$) | | | | | | Date | Optimal NV Flow Rate ($m^3/s$) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 20:00 | 22:00 | 24:00 | 02:00 | 04:00 | 06:00 | | 20:00 | 22:00 | 24:00 | 02:00 | 04:00 | 06:00 |
| **08/20** | 0 | 0 | 0 | 0.625 | 0.875 | 0.625 | **08/23** | 0.125 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 |
| **08/21** | 0 | 0 | 0 | 0 | 0 | 0 | **08/24** | 0 | 0.125 | 0.125 | 0.125 | 0 | 0 |
| **08/22** | 0 | 0 | 0 | 0 | 0 | 0.625 | **08/25** | 0 | 0.125 | 0.125 | 0.25 | 0 | 0 |



(a) Outdoor air temperature and relative humidity; (b) Cooling load;

**Figure 5**: Results for "offline" MPC – multiple days simulation

# 5. SUMMARY OF FINDINGS AND RECOMMENDATIONS FOR FUTURE WORK

This paper presents a transient thermal model for a building with mixed-mode cooling, which is used within an offline MPC framework with GenOpt as an optimizer. The main findings of the study can be summarized as follows:

- Simulation results for a typical day and six successive days indicate that the optimal selection of ventilation time and the corresponding flow rate from the MPC controller combined with coordinated control of solar gains (shading devices) is an efficient way to improve the effectiveness of night cooling. The cooling load on the following day can be significantly reduced or offset.
- The control sequences are highly dependent on building design parameters (exposed thermal mass, window-to-wall ratio, orientation, etc.) and weather conditions, confirming the need for anticipatory control strategies in order to enable optimal performance.

Significant work on MPC for buildings with mixed-mode cooling is currently in progress including a generic identification approach for developing a reduced-order model considering the nonlinearity caused by natural ventilation as well as integration with more advanced HVAC systems (mechanical cooling mode).

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## APPENDIX

**Table A:** Natural convection correlation

| Walls | "Hot floor" or "Cold ceiling" | "Cold floor" or "Hot ceiling" |
|---|---|---|
| $h_n = 1.31\left\|\Delta T\right\|^{1/3}$ | $h_n = \dfrac{9.482 \cdot \left\|\Delta T\right\|^{1/3}}{7.283 - \left\|\cos\Sigma\right\|}$ | $h_n = \dfrac{1.810 \cdot \left\|\Delta T\right\|^{1/3}}{1.382 + \left\|\cos\Sigma\right\|}$ |
| With "Hot" and "Cold" indicate the comparison with air temperature | | |

**Table B**: Composition of building elements and thermal properties of building materials

| | | **Thickness (cm)** | **Thermal conductivity (w/m·°C)** | **Specific heat (kJ/kg·°C)** | **Density (kg/m$^3$)** |
|---|---|---|---|---|---|
| **External wall** | **inside** | | | | |
| | **Gypsum** | 1.27 | 0.17 | 1 | 800 |
| | **insulation** | R=4.4 m$^2$·°C/w | | | |
| | **Brick** | 10.2 | 0.722 | 0.835 | 1922 |
| | **Outside** | | | | |
| **Internal wall** | **Plaster** | 1.58 | 0.23 | 1.05 | 593 |
| | **Block** | 10.2 | 0.722 | 0.88 | 961 |
| | **Plaster** | 1.58 | 0.23 | 1.05 | 593 |
| **Floor (ceiling)** | **Floor tile** | 0.64 | 0.519 | 1.05 | 1602 |
| | **Concrete** | 5, 10, or 40 | 1.7 | 0.8 | 1700 |
| | **(air gap)** | R=0.16 m$^2$·°C/w | | | |
| | **Acoustic panel** | 2 | 0.21 | 0.9 | 800 |

# A PROBABILISTIC APPROACH TO NONSTRUCTURAL FAILURE

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## ABSTRACT

In spite of a virtual epidemic of *nonstructural* failure (leaking roofs, delaminating finishes, etc.), there is no method for architects to assess the reliability of nonstructural elements within the buildings they design. Structural elements and systems within buildings, on the other hand, are designed so that the probability of failure is acknowledged. The analysis of nonstructural building elements and assemblies is more complex, and raises different issues, than that of structural elements and systems. This paper suggests areas for future research into the probabilistic design of nonstructural building elements by examining the limit states and performance requirements for nonstructural failure (risk assessment); the boundaries of sites within which failure might occur (probabilistic analysis); whether a probabilistic approach to nonstructural failure makes sense; and the consequences of peculiarity and redundancy.

Keywords: failure, nonstructural, probability, reliability, risk

## INTRODUCTION

It is commonly acknowledged that nonstructural parts of buildings fail at an alarming rate: roofs leak, flooring delaminates, paint peels, and so on (Chen *et. al.,* 2010). If the definition of nonstructural failure is extended to include things like slabs that are not flat, or enclosures that are not energy-efficient, or rooms that function poorly for their intended purpose, or improperly constructed elements that need to be removed and reconstructed, or any number of other criteria for failure, then the rate of failure undoubtedly increases.

Surprisingly, given this virtual epidemic of nonstructural failure, there is no method commonly encountered in practice for architects—even conscientious ones—to assess the reliability of the buildings they design. Of the construction products, systems, and methods that are sanctioned by building codes and available on the marketplace, none provide data from which the reliability of the assemblies into which they are fashioned can be ascertained. Moreover, there are few if any adequate statutory controls based on risk assessment, and there are numerous instances where design entities requiring serious engineering (e.g., building enclosure systems) are left to “the architect who generally specifies, details, and approves” such things, often leading to “significant problems with the façades of modern buildings” (Faddy *et. al,* 2003).

If this state of affairs existed for the structure of buildings (structure referring to the columns, walls, beams, and slabs that together resist various forces impinging upon the building), it would be impossible to know whether any given building had an unacceptable risk of collapse. Both life and property would be in danger, and both would be endangered to an extent that was not possible to determine either in the aggregate (e.g., for society as a whole) or in any particular instance (e.g., for the building you are in right now). The analysis of nonstructural building elements and assemblies is more complex, and raises different issues, than that of structural elements and systems. It is the purpose of this paper to examine nonstructural reliability, suggesting areas for future research.

## RISK ASSESSMENT

Building elements will *fail,* and their failure can be understood *probabilistically*. When journalists and others use phrases that are implicitly probabilistic ("Excess capacity in the economy may well dampen cost and price pressures for a period..."), it is easy to conclude that they are simply hedging their bets. By stating that excess capacity may well dampen price pressures, one can conclude with equal certainty that excess capacity may well *not* dampen price pressures. In other words, something *may* happen, or it *may not* happen. We are left with nothing but the appearance of wisdom.

Yet probabilities can be useful, even when they correspond not to a classic, well-defined random occurrence (e.g., rolling dice or flipping coins), but to subjective, expert opinion (e.g., there will be a 30% chance of rain tomorrow). Such expert opinion, especially when encountered in building science, may be based purely on a kind of epidemiological or actuarial approach—where the historic incidence of a particular outcome is used to extrapolate about the probability of future occurrences—or may draw on both historic rates of occurrence as well as underlying causal hypotheses.

In the case of structural failure, building codes make assumptions based on evidence assembled from laboratory tests and from the performance-history of large groups of structures, without having any specific knowledge about the likelihood of failure for any particular proposed building. However, by tracking the number of structural failures over time, code agencies (and politicians who turn model codes into legal rules and regulations) can make judgments about the efficacy of legislation and can rationally modify such legislation when new information is generated, typically in the wake of disasters like earthquakes, hurricanes, or even man-made attacks. Yet such strategies are rarely employed for nonstructural building elements.

### Limit states

MacGregor (1976) discusses the concept of limit states to define various criteria for which structures must be designed. In "limit states design the designer is expected to identify all the critical limit states and consider them either explicitly by design checks or implicitly by satisfying certain detailing requirements or minimum reinforcement requirements. Ideally, the limit states would be expressed in terms of performance requirements which are essentially independent of the structural material."

Structural design is not limited by a single mode of failure; rather, there are several criteria (limits) that must be checked, including yielding or rupture (whether due to tension, compression, or shear) and deflection or deformation. Still, the types of limits are fairly well-defined; variations in material and geometric properties are, for the most part, regulated and tabulated within state-sponsored building codes based on the work of consensus-driven institutes and associations; and techniques have been developed to analyze and design structures so that they remain within their limit states. In contrast to the relative simplicity of structural limits, analogous limit states for nonstructural failure are far more diverse, and techniques to analyze and design for such limit states are much harder to find. Such nonstructural limits include things like water intrusion, air intrusion, vapor-condensation, heat loss, bowing, cracking, peeling, as well as any number of serviceability-type issues: noise, vibration, glare, and so on. Not only are nonstructural limit states more diverse, but the number of different materials and potentially damaging material interactions—especially when exposed to diverse environmental conditions—is far greater for nonstructural, than for structural, building elements.

Given the multiplicity of both limit states and material/environmental interactions, the question remains whether it is possible, or feasible, to establish the equivalent of "design strengths" (i.e., limiting values based on specified levels of risk) for nonstructural construction elements, and to develop corresponding design methods. Aside from the enormous task of identifying and documenting failure probabilities for all material interactions and all known limit states, additional difficulties would need to be overcome, including the following:

1. Product specifications may refer exclusively to particular proprietary or nonproprietary systems, in spite of the fact that such systems may not be entirely self-sufficient. In other words, a system may need to connect to other systems at its boundary, and the entire range of possible boundary conditions may not be specified or tested.

2. Systems may be used or configured in ways that differ from what has been tested and approved by manufacturers (much like the use of "off-label" drugs in medicine).

3. All possible modes of failure, and all possible combinations of these failure modes, are not always addressed within system specifications.

4. Idealized, specified conditions (including the required cleanliness of material surfaces, the prevailing temperature and humidity during installation, the required coverage of adhesives or heat welding, and so on) may not be met; and, equally important, there may be no systematic means either to certify compliance or to test, after the fact, whether the installed product satisfies the specifications.

**Probabilistic analysis**

In order to be more precise about the risk of failure, it is useful to define the boundaries of sites within which failure might occur. Depending upon the type of failure, such sites might be dimensionless quantities (e.g., *number* of penetrations in an air barrier) or else the familiar dimensional measures for various geometric objects (e.g., *length* of seams in an EPDM roof; *area* of paint on a flat surface; or *volume* of contaminated air in a room). A particular quantity could then be chosen to define the nominal magnitude for each site (e.g., 1 m.; 100 $ft^2$; 50 gal.) so that it can be systematically evaluated and compared, and so that rational standards for reliability can be developed. Methods for determining system reliability, while well-established, are quite complex and beyond the scope of this paper. For an overview of reliability computation methods and strategies, see Blischke and Murthy (2003).

**Site, events, and event density**

If we call every potential site of nonstructural failure, along with its mode or modes of failure, an *event*, it is useful to distinguish between negative outcomes that are independent of the number of events, and negative outcomes whose likelihood of occurrence increases with the number of events. In the first case, a particular event (e.g., the bringing together of incompatible materials, or the use of an item with insufficient strength or durability) *will* result in failure, whether it occurs only once or numerous times. The mechanism of failure guarantees a negative outcome. Yet even with this certainty of failure, the overarching probabilistic framework for understanding failure remains valid: whether the causes of failure were due to errors in the drawings and specifications created by the architects and design consultants, or by errors in fabrication or installation, or by any other action, it is often only in retrospect that one can say that a particular event was certain to cause failure. Without this knowledge, all one can say is that a building *might* fail, or has a probability of experiencing failure. This type of failure is independent of "scale" or complexity—a greater number of similar events does not increase the chance of failure, but only increases the number of failure events.

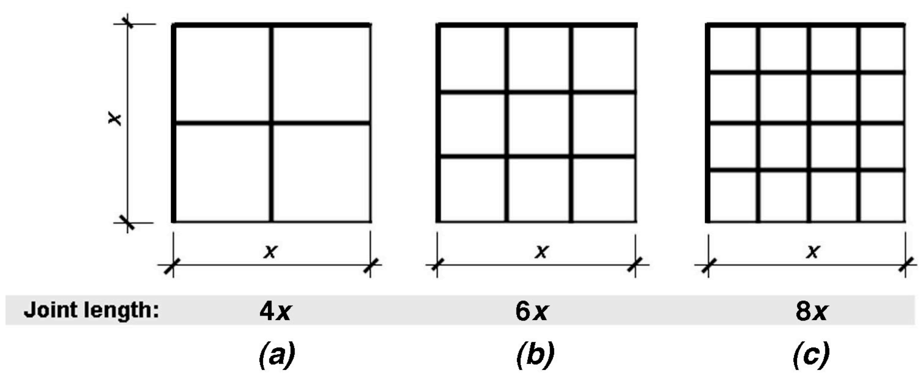


**Figure 1.** Abstract representation of variable joint length

In the second case, a particular building element may not be intrinsically predisposed to fail, but rather may have a chance of failure based on the combined influence of any number of variables. Depending on the mechanisms or modes of failure that correspond to these variable conditions, the probability of failure can be determined in relation to the number of times that such events occur, that is, in terms of the *event density*. For example, in the case of a sealant joint between two panels whose integrity over time depends only on a single variable (let's say that this variable is the proper installation of a backing rod with integral bond breaker), and if the variable is well-defined and random (that is, if there is an equal likelihood that the backing rod at any site—e.g., along any given linear foot of the joint—will be properly installed), then the probability of failure is proportional to the total number of sites, i.e., to the total length of joints.

For the joints abstractly represented in Figure 1 (shown with bold lines), a given panel size is subdivided in three different ways (cases *a, b,* and *c*) such that the total joint lengths are 4*x,* 6*x,* and 8*x* respectively. The probability of failure is therefore one and a half times as great in case *b* as in case *a,* and two times as great in case *c* as in case *a*.

**Multiple failure modes**

On the other hand, there may be more than one variable in play, each of which has some likelihood of causing joint failure independent of the other. Because so many different modes and manifestations of architectural failure—condensation, leaks, cracks, corrosion, deterioration, mold, etc.—are potentially present at every building failure "site," and because these possible modes of building failure are often *not* mutually exclusive, the probability of failure does not increase proportionally, but rather geometrically or even exponentially, when multiple modes of failure are considered.

For example, the integrity of the joints in Figure 1 may be threatened not only by improper installation of a backing rod with integral bond breaker, but by the cleanliness of the panel surfaces to which the sealant is directly adhered. If it is assumed that the probabilities of each separate outcome are the same and not mutually exclusive, then the chance that a given length of joint will fail by *either* of the failure mechanisms is double the probability that the joint will fail if only one of the failure mechanisms is in play. In other words, the probability of failure is four times as great in case (*c*), with both failure mechanisms in play, as in case (*a*), with only one failure mechanism in play.

Assuming that each failure mode has the same probability of experiencing a failure event, the overall probability of failure increases exponentially as both the number of non-mutually-exclusive failure modes and the building's complexity or event density (in this case modeled as a simple increase in the length of joints) increase linearly. That is:

$$P(F_c) = n_o n_m p \tag{1}$$

where

- $P(F_c)$ = the overall probability of experiencing a failure event (with constant probabilities of failure)

- $n_o$ = the number of occurrences (event density)

- $n_m$ = number of independent failure modes

- $p$ = the probability of experiencing a failure event for any one mode of failure for a single occurrence (event density = 1)

A building with a single failure mode and an event density of 1 has a probability, *p,* of experiencing a failure event; doubling both the number of failure modes and the event density results in an increase in the probability of experiencing failure events to 4*p*; tripling both the number of failure modes and the event density results in a probability of 9*p*; and quadrupling both the number of failure modes and the event density results in a probability of 16*p*. This pattern can be clearly seen in Table 1.

**Table 1.** Probability of failure events in relation to event density and failure modes*

| Number of failure modes | Assumed probability of failure event | Relative number of occurrences (event density) | | | |
|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 |
| 1 | for mode 1 = *p* | *p* | 2*p* | 3*p* | 4*p* |
| 2 | for mode 2 = *p* | 2*p* | 4*p* | 6*p* | 8*p* |
| 3 | for mode 3 = *p* | 3*p* | 6*p* | 9*p* | 12*p* |
| 4 | for mode 4 = *p* | 4*p* | 8*p* | 12*p* | 16*p* |

* Assuming each failure mode has an equal probability of failure within an occurrence space.

While these results assume that each mode of failure within a given occurrence space has an equal likelihood of producing a failure event, similar conclusions can be drawn from a more general formulation of the problem in which probabilities of failure for each failure mode within an occurrence space may vary. In that case, we get:

$$P(F_v) = n_o \sum_{n=1}^{n_m} p_n \quad (2)$$

where $P(F_v)$ is the overall probability of experiencing a failure event (with variable probabilities of failure), the other parameters as defined for Equation 1.

The combination of multiple failure modes along with increasing building complexity (event density) results in an increasing probability of failure. Where multiple failure modes are found to occur together at a site, it might be possible to group them as a *single event* whose probability of failure equals that of the various individual failure mode probabilities combined. However, there are several types of failure mode interactions where such an assumption does not apply:

1. In some cases where two or more modes combine, the failure probability *increases* beyond what would ordinarily be expected. For example, hurricane conditions with wind driven rain (mode 1) and wind-borne debris (mode 2) each carry an independent potential for damage. However, debris that breaks glass in the context of wind-driven rain will carry *more* risk of failure than what would be calculated for each mode of failure considered separately (i.e., with the two probabilities of failure simply “added” together).

2. In some cases where two or more modes combine, a failure probability comes into play where none previously existed—that is, where *no failure modes per se* existed until they combined to create a new failure mode. An example would be two metals that are in contact ("mode" 1) along with an electrolyte such as water that is present on the surface ("mode" 2). Two innocent practices (neither of which is a problem considered in isolation), when combined, create a new failure mode (galvanic corrosion).

3. In some cases where two or more modes combine, the failure probability actually *decreases* compared to the two modes acting separately. For example, deploying redundant layers, each of which when considered separately has a probability of failure

proportional to some measure of quantity (e.g., length, or area), may actually result in a lower probability of failure. Storm windows and double sealant joints create a greater quantity of joints with the potential to fail, yet result in a decreased probability of failure. In such cases employing redundancy, the overall risk of failure is no longer necessarily defined by the addition of the separate probabilities. As an extreme example, consider a roof membrane where manufacturing defects (holes) have a 0.1 probability of occurring within a given unit area. If two such units of area are deployed side by side, the overall chance of failure doubles from 0.1 to 0.2. But if the two membranes are placed one over the other, so that failure only occurs when holes in each membrane align, the chance of having two such holes (one per membrane) within the same unit of area decreases to 0.01, and the chance of such holes actually aligning (the precondition for failure) is even smaller.

## DOES A PROBABILISTIC APPROACH MAKE SENSE?

It is apparent that not only are nonstructural failures costly and inconvenient for building owners and users, but that the risk of such failure is difficult or impossible to determine by those responsible for the design of buildings. Does it follow that the "status quo" method of *not* considering the probability of nonstructural failure should be replaced with a probability-based method? Whether or not a risk-based approach results in lower, or at least more predictable, life-cycle costs, a number of potentially countervailing issues must be considered.

### Legal/constitutional/political issues

Structural design methods incorporating a probabilistic strategy to control failure are not only promulgated by not-for-profit code councils and industry-sponsored institutes (ICC, AISC, AITC, ACI, etc.), but are also adopted by governmental entities in the form of building codes, thereby becoming legally binding and enforced by state power. On the other hand, property owners and builders—supported by the political and legal infrastructure—have sometimes been able to successfully block both structural and nonstructural initiatives that would increase safety but also increase costs. In the case of nonstructural initiatives that might not only increase costs, but also restrict design choices, courts may well strike down provisions constraining the freedom of architects, manufacturers, and property owners in cases where a countervailing “health, safety, and welfare” societal benefit is not sufficiently evident.

### Cost-benefit issues

MacGregor (1976, Fig.19) breaks down the cost of building structures into three components: "production," "maintenance," and "insurance." When production and maintenance costs decrease beyond a certain point (corresponding to increasingly dangerous building structures), insurance costs increase dramatically, presumably reflecting the increasingly untenable risks that arise when the costs of providing adequate structural safety are not met. Thus, the added costs brought about by governmental intervention to promote structural safety have the benefit of reducing costs associated with loss of life and property; and the benefit is arguably greater than the cost. Whether the same sort of calculation can be made for nonstructural building elements is less clear. Among the significant costs of structural collapse are loss of life, and loss of the building's ability to function, neither of which is intrinsic to nonstructural failure (Faddy *et. al.,* 2003, p. 113). It is possible that it is cheaper to repair failed nonstructural building elements as these failures become manifest, than to anticipate all possible failure modes in advance and to design and construct buildings with a predetermined risk of failure.

**Problems with obtaining data**

Manufacturers are not required, and are not generally interested, in publishing data about the reliability of their products, even if there were standards for how to do this. For one thing, competition with other manufacturers, and the absence of mandatory disclosure based on established protocols, favors hyperbole over accuracy. In addition, manufacturers are often unwilling to evaluate or describe the behavior of their products in relation to adjacent or connecting products over which they have no control.

# CONCLUSIONS

The probabilistic nature of building failure is well understood in structural engineering, where factors of safety are explicitly calibrated in such a way that structures fail at a desired rate. It is understood that avoiding all structural failure is not possible; the intention is therefore to reduce (or increase) the probability of failure to a politically/economically acceptable rate. Refinements in structural design methods have made the risk of failure more uniform—less subject to differences in materials or types of loads. Whereas the probability of structural failure (i.e., the actual collapse of buildings or structural components like beams or columns) is made explicit within the design methods enforced by building codes and, in fact, forms the very basis of structural design, the design of nonstructural parts of buildings has no underlying probabilistic basis. That is, when architects create drawings and specifications for buildings, they have no basis for determining the probability of nonstructural failure. A probabilistic basis for such failure is acknowledged neither in theory nor in practice. Nevertheless, it is still possible to draw some important conclusions about the nature of such failure, and point towards future areas of research.

**Peculiarity and complexity**

Perhaps the most important conclusion derives from the fact that, for *unusual* (peculiar or complex) architectural designs, the interaction of materials, systems, geometries, environmental conditions, installation methods, and so on, is rarely systematically tested or theoretically grasped. Conventional construction details and methods, on the other hand, have at least a track record of generally successful (or unsuccessful) application. While the lack of a consistent measure of reliability applies to such conventional systems as well, there is at least an informal understanding of how such systems perform over time. For this reason alone, one can state that *nonstructural failure will generally increase as the peculiarity or complexity of the architecture (i.e., the deviation of its design from well-established norms) increases.*

This conclusion requires a disclaimer: it presupposes an ordinary level of attention given to all aspects of building design and construction. In other words, it is assumed that little or no original research is undertaken to establish the behavior of unusual design elements or their interactions. The nonstructural failure of the John Hancock Tower in Boston may serve as an example of a building designed with unconventional curtain wall details, but without adequate testing and research (Campbell, 1988). Of course, if one has the budget, the time, and the expertise, it is certainly possible to reduce the probability of failure when designing unusual or complex buildings. An example of such an attempt can be seen in the glass enclosure system developed for La Cité des Sciences et de l'Industrie in Paris as described by Rice (1995).

**Redundancy**

The benefit of redundancy, examined from a probabilistic standpoint, is a relatively unexplored and potentially fruitful area of research. In the hypothetical and schematic example cited earlier, providing two roof membranes instead of one doesn't merely cut the risk of failure in half, but rather decreases the risk of failure by an order of magnitude. Of course, it is crucial that any strategy employing redundancy take into account the specific mode of failure: adding an extra (redundant) layer of paint over an improperly prepared substrate confers no particular advantage since the utility of the redundant layer depends on the integrity of the layer below. In other words, the conditional probability of failure of the redundant layer, given failure of the layer below (and therefore failure of the system as a whole), is 1.0, conferring no advantage. At the other extreme, the conditional probability of system failure for the two membranes discussed earlier, each membrane having a failure probability of 0.1, is $0.1 \times 0.1 = 0.01$, a significant improvement.

Conventional practices, such as the provision of roof overhangs, can be reevaluated in this light. For a given exterior wall surface area, if the probability of failure due to water intrusion through an unintended hole in the wall is, say, 0.05, and if the probability that wind-driven rain will reach that wall surface is 0.07 when an overhang is in place, then the conditional probability of failure with an overhang is $0.05 \times 0.07 = 0.0035$, a dramatic reduction in risk compared with the hypothetical failure probability of 0.05 without the overhang.

**Limitations of traditional architectural drawings and specifications**

Architectural drawings do *not* attempt to represent each nonstructural element and its conditions; rather, general descriptions and notes apply to large conglomerations of elements, under the assumption that all the various conditions actually encountered, but not specified, will be somehow dealt with in the field. To the extent that this practice is not remedied through comprehensive and carefully checked shop drawings, it constitutes a major deficiency in the process of architectural construction.

Typical building specifications do not supply consistent, and useful, instructions for building contractors. Instead, advice like this is common: "...it is essential to ensure the substrate is structurally sound, clean, and dry. Prior to the installation, the surface should be protected and free of any potential substance or debris that might reduce or prevent adhesion" (Miller, 2011). Unfortunately, nothing in such specifications provides a method, a protocol, or a test to ensure that the desired conditions are met. It is as if such paragraphs were written by lawyers, hoping to establish a basis for successful litigation in the event of building failure, rather than by architects and engineers seeking to actually create conditions that will reduce and control the probability of failure. Yet even conventional tests are problematic, as they are not designed to provide data from which the risk of failure can be determined. Any curtain wall assembly can be mocked up and tested per ASTM guidelines, but it is *not* feasible to construct 500 such mock-ups in order to get a sense of the actual risk of failure.

Performance based criteria, especially those that cannot be explicitly measured ("ensure that the substrate is structurally sound") rely on the conscientiousness and expertise of architects and builders who most often lack the tools, and in many cases may prefer not to jeopardize their firms' profitability by expending discretionary resources, to determine the failure risk of the assemblies they design and build. What seems clear is that prescriptive mandates—designed so that builders and architects use assemblies, systems, or products engineered according to explicit probabilistic criteria for failure—are most likely to reduce the current epidemic of nonstructural building failure.

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# ASSESSMENT OF THE QUALITY STEEL REINFORCEMENT BARS AVAILABLE IN NIGERIAN MARKET.

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**ABSTRACT**.

The use of substandard and steel reinforcement rods in the construction of structural steel concrete elements of a building, most especially in floor slabs has been identified as one of the most important causes of structural failures in buildings in Nigeria. This research investigated the mechanical properties (yield strength, ductility and the ultimate tensile strength) of 12mm diameter steel bars commonly used in reinforcing floor slabs using an extensometer. Results obtained from the tests showed that only three (3) brands out of a total of nine (9) tested most commonly used brands of sampled rods showed yield strengths greater than 460N/mm$^2$. The yield strengths obtained range between 337.72 N/mm$^2$ and 569.71 N/mm$^2$. The study confirmed that the wide usage of substandard steel reinforcement bars in the Nigerian market is a major contributing factor to increasing incidences of structural building failures in the country when viewed from the angle of variability in material quality.

**Key words**: Nigerian-steel, Rebars, Reinforcements and Steel-bars.

## BACKGROUND TO STUDY.

From pilot survey in Lagos, it was discovered that over ninety percent (90%) of storey buildings in Nigeria are structures whose structural frame/elements are made of reinforced concrete. The place of reinforced concrete in the Nigerian construction industry cannot be over emphasized and in fact, bulk of her construction industry revolve around the use of concrete, be it in dams, bridges, buildings and all other civil engineering works.

According to Ede (2010), the occurrence and casualties of building collapse from the year 2000-2010 was alarming. Of the three (3) states in Nigeria with the highest number of building collapse, about 80% of the collapse and 65% of the casualties (deaths) occurred in Lagos state with forty (40) and one hundred seventy five (175) collapse and deaths respectively. Over 95% of the collapse occurred in over two (2) storey buildings.

Oni (2011) also used the predictive linear trend equation to show that an average of ninety-one (91) storey buildings will collapse between the years 2007-2017 with an average of nine (9) collapses annually.
Also, Oke and Abiola-Falemu (2009) showed that poor material and workmanship contributes about 52% to the overall causes of building collapse in Nigeria.
Ogunsemi (2002) also showed that poor workmanship amount to about 18.4% of the total causes of building collapse while the use of sub-standard materials amount to 18.4% of building collapse in Nigeria but Oke and Abiola-Falemu (2009) asserted that their study of 52% overrides others because they based theirs on a greater number of building collapse data than the others.
It can be deduced from the above percentages from Ogunsemi (2002) and Oke and Abiola-Falemu (2009) that about 26% of building collapse occurred as a result of the use of substandard materials.

Holistically, buildings can never collapse until the structural component(s)/systems fails or begin to fail and since over 90% of the structural components/systems in Nigeria are made of concrete, it can be deduced that the greatest percentage of collapse is as a result of concrete failure and 26% of this failure is as a result of the use of substandard material. Reinforced concrete star materials are cement, aggregates (fine and coarse) and steel reinforcement rods.
There arises a need to study the qualities of these star materials in an attempt to curb or reduce to the nearest minimum the menace of collapse due to the use of substandard materials.

## Building.

According to the United States Building Seismic Safety Council and the Federal Emergency Management Agency (2010), a building is simply an enclosure intended for human occupancy and or other uses. This enclosure ranges from simple bungalows to multi-storey buildings with over a hundred numbers of floors. It further divides buildings into two main broad components which includes the structural component which bears the whole weight of the building and effectively transmit it to the ground, e.g. slabs, beams, columns and foundation; and non-structural components that simply bears its own weight and transmit its weight to the structural components, e.g. partition walls, electrical and mechanical installations, windows, doors, etc.

An example is the tallest building in the world, Burj Khalifa with reinforced concrete as its primary supporting structure. The building is 829.84m high with 163 floors and structural concrete supports the floors to the 156$^{th}$ floor above which the remaining supporting structure to the top is mainly of steel.

It can be seen that the role of reinforced concrete as a structure cannot be over emphasized.

## Basic Functional Requirements of Building Structural Components.

Olusola *et' al* (2011) summarized the basic requirements that a structure must satisfy and they include the following:

1. Each and every member of a structural system should be able to resist, without failure or collapse, the applied loads under service conditions. In other words, it must possess adequate strength. This demands that the material that make up the structure, like concrete, steel sections or wood, must be adequate to resist the stresses generated by the loads and the shape and size of the structure must be adequate.

2. Every component of the structure should be able to resist deformation under loading conditions. Deformation implies a change in size or shape when a body is subjected to stress. Excessive deformations that are deformations exceeding specified acceptable limits will impair the functional performance of a structure and any attached services. This demands that the stiffness of a beam or column is a measure of its resistance to bending or buckling. It should be noted that a component may be strong and not stiff, and vice-versa.

3. Every component of a structure must be stable otherwise the whole structure is assumed to be unstable. Structural stability is needed to maintain shape. It is the ability of a structure to retain, under load its original state of equilibrium. It can mean anything from resistance to a minor degree of movement to resistance to sliding overturning partial or complete collapse. Any phenomenon (which will be a potential source of load) that can alter the load-carrying behaviour of a structure, if not properly taken care of can lead to instability, a condition in which the support reaction is less than applied load. Thus to ensure stability, loads must be balanced by reaction, and the moments due to loads must be balance by the moments due to reactions.

As it can be observed from the above that in the event of failure in the structural component(s) of a building, the failure of such building is inevitable. The structural components define the strength and stability of the building.

## Reinforced Concrete as a Structural Material in Nigeria

The four (4) main materials that these structural components are made up of are masonry (load bearing walls), timber, steel and plain/reinforced concrete (Garrison, 2011). Some structural elements derive their nomenclature by the materials they are made from, e.g., reinforced concrete beam, steel columns, timber joists, etc.

From previous survey within Lagos, it was observed that over ninety percent (90%) of storey buildings (buildings with floor(s) above the ground floor) are structures whose structural system/elements are made of reinforced concrete. The place of reinforced concrete in the Nigerian construction industry also cannot be over emphasized and in fact, bulk of her construction industry revolves around the use of concrete.

Also, structural materials are components capable to bear load due to their ability to resist stresses. Structural material are components that determines the strength of a building, they are responsible for the stability of the structure.
There are several structural materials like timber and masonry-network but when buildings needs to go higher, they are simply incapable of bearing the resulting stresses due to the imposed/dead loads and this limits structural components to two major materials which are steel and reinforced concrete.
Steel is a material that is good in resisting both compressive and tensile stresses but unlike steel, concrete is only good in resisting compressive stresses but structural components are concurrently subjected to both tensile and compressive stresses and for concrete to serve as a very good structural material, it must be able to resist tensile load and to achieve this, it is usually reinforced with materials that are good in resisting tension and these materials include fibre usually sourced from plants, glass fibres and steel. This introduces concrete to a composite referred to as reinforced-concrete in which the concrete resist the compressive stresses and the other composite resisting the tensile stresses in the tensile zone of the component under its service load.
In building construction today, steel bars are the most widely used reinforcing material in concrete largely because concrete bonds well with steel and both expand and contract to about the same degree with temperature changes (Committee E-701, 2006). And probably also because it has more strength and durability advantages than others.
In light of the above, the study of structural materials in this study will be limited to reinforced concrete.

## The Role of Component Materials Quality on the Performance of Structural Reinforced Concrete.

It is widely recognized that reinforced concrete strength depends on the strength of cement paste, on the cement paste-aggregate bond, on the aggregate strength and on the strength of its reinforcing material. For ordinary concrete, the strengths of paste and the paste-aggregate bond control concrete strength (Lamond and Pielert, 2006).
The factors that can greatly affect the strength and durability of reinforced concrete are the quality of its constituent materials and production.
The use of low quality materials results in low quality concrete and even when high quality materials are used but combined in wrong proportions, badly produced, it can result in the production of undesirable reinforced concrete properties.
The material make-up/components of reinforced concrete include:

- Cement
- Aggregate (fine and coarse)
- Admixtures (Chemical and Mineral) and
- Water and
- Steel reinforcement.

But this study will be limited to the contributions of steel rebars on the properties of reinforced concrete in Nigeria.

## Roles of reinforcing steel in concrete property.

- **Strength**
  Concrete is best at compression and its resistance to tension is negligible and therefore, in reinforced concrete structural elements under service conditions, concrete resist only compressive stresses and the steel rebars resist both tensile and compressive stresses in the tensile and compression zones of the stress block respectively. The greater the yield strength of the rebars, the greater the strength of the reinforced concrete structure.

- **Ductility.**
  All structures need ductility, as well as strength. In reinforced concrete, it is the reinforcing steel that induces ductility into the structural element. Ductility of the structural reinforced concrete element is its ability to fail by deflection or extensive cracking in an overload situation, without sudden catastrophic collapse. This failure mode saves lives by giving adequate warning before collapse. The ductility property of reinforced concrete structure is imputed by the steel rebars. Concrete is considered a brittle material but when reinforced with steel (reinforced concrete), it exhibits some measure of ductility. The level of ductility of reinforced concrete structural element is determined by the ductility (elongation) of the rebars.

The factor that undermines the effects of reinforcing steel rods in reinforced concrete includes:

- When the steel bar strength is below the designed yield and ultimate strength;
- Ductility of the rebars (usually measured by elongation).
- Corrosion of the reinforcing steel rods under its service load; and
- Loss of bond between the steel rods and concrete.

These factors can be ameliorated by controlling the chemical composition of the rebars from the manufacturing process as the properties of rebars are influenced by the chemical composition of the steel from which it is manufactured. Table 1.2 shows the influence of the various rebars chemical components on the resulting steel (Prabir C. B. *et al*, 2004).

Deficiency in the main chemical components and level of impurities can result in the production of substandard steel rebars.

## Reinforced concrete design assumptions.

The design of reinforcement in concrete to BS 8110:1997, the yield strength of steel is taken to be 460N/mm$^2$ and the current EuroCode2 (EC2) now states that the yield strength of steel be 500N/mm$^2$. The specification for steel reinforcement for concrete to BS4449:2005 states that the minimum steel yield strength be 500N/mm$^2$. The Nigerian standard as specified by the Nigerian Industrial Standard, NIS 117:2004 specify the yield strength of steel Grade 420 to be 500N/mm$^2$

If steel reinforcements in reinforced concrete are designed based on these design values and the actual steel available for constructions falls below these strength values, the failure of such structures is almost certain. It is on this premise that the need arose to study the quality of steel reinforcement in the Nigerian market to ensure it's not one of the factors contributing to building failures/collapse in Nigeria.

**Table 1.2:** Influence of different chemical ingredients in steel on properties of rebars (Prabir *et al*, 2004).

| **S/N** | **Chemical** | **Effect on rebar** | |
|---|---|---|---|
| | | **Controlling property** | **Actual effect** |
| 1 | Carbon (C) | Hardness, strength, weldability and brittleness | Higher carbon contributes to the tensile strength of steel, that is, higher load, bearing capacity and vice versa. Lower carbon content less than 0.1 percent will reduce the strength. Higher carbon content of 0.3 percent and above makes the steel bar unweldable and brittle. |
| 2 | Manganese (Mn) | Strength and yield strength | The manganese content in steel is not specified as per IS: 1786.<br>However higher manganese content in steel increases the tensile strength and also the carbon equivalent property. |
| 3 | Sulphur (S) | Present as an impurity in steel which increases its brittleness | Presence of sulphur should be limited as per IS: 1786. Presence of higher sulphur makes the bar brittle during twisting, as higher sulphur content brings the hot shot problem during rolling. |
| 4 | Phosphorus (P) | Present as an impurity which increases strength and brittleness | Higher phosphorus content contributes to the increase in strength and corrosion resistance properties but brings brittleness due to the formation of low euctoid phosphicles in the grain boundary. Also lowers the impact value at sub zero temperature level (transition temperature). |
| 5 | Copper (Cu) | Strength and corrosion resistance properties | Being a pearlite stabiliser, it increases the strength and corrosion resistance property. |
| 6 | Chromium (Cr) | Weldability and corrosion resistance | Present as an impurity from the scrap and influences carbon equivalent;<br>weldability and increases corrosion resistance property. |
| 7 | Carbon Equivalent (CE or Ceq) | Hardness, tensile strength and weldability | This property is required to set the cooling parameters in Thermo Mechanically Treated (TMT) process and a slight variation in carbon equivalent may alter the physical properties. In case Of Cold Twisted Deformed (CTD) bars, carbon equivalent has a maximum limit of 0.42 percent but there is no lower limit prescribed. As such, as long as the chemical composition and physical properties of raw materials are within specified limits, the variation in carbon equivalent as in the case of TMT bars. |

# METHODS

## Sampling and Testing

The method of sampling these rebars is by market survey to identify the steel brands used in Lagos, purchased three cuts of 12mm diameter rebars for each identified steel brand from three different shops. The cuts were labeled and sent to the laboratory for tests. 12mm diameter bar size was chosen because it is the most used in structural design work in Nigeria.

Nine (9) steel brands were identified denoted as Brands 1-9 as shown in Fig. 1-3. The tests conducted include tensile yield and ultimate strengths and elongation; and prices per standard market length of the identified brands were also surveyed. The results are as shown in Fig. 1-3.

# RESULTS

The tensile strength test and elongation were conducted on each sample with the extensometer and the results are tabulated in Fig.1-3.

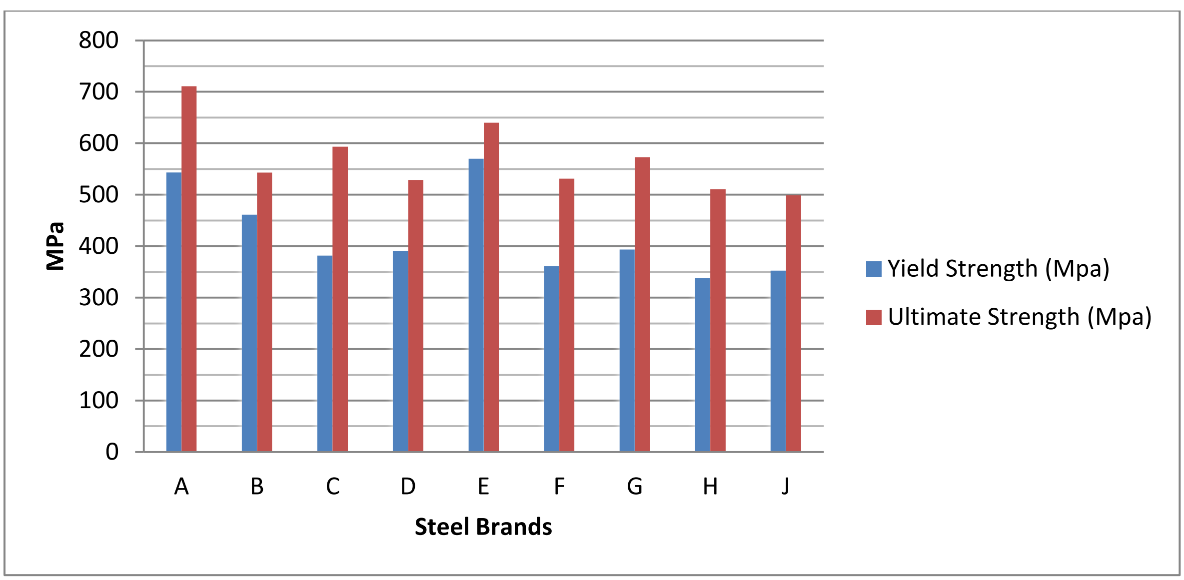


**Figure 1:** Steel Brand's yield and ultimate strengths.

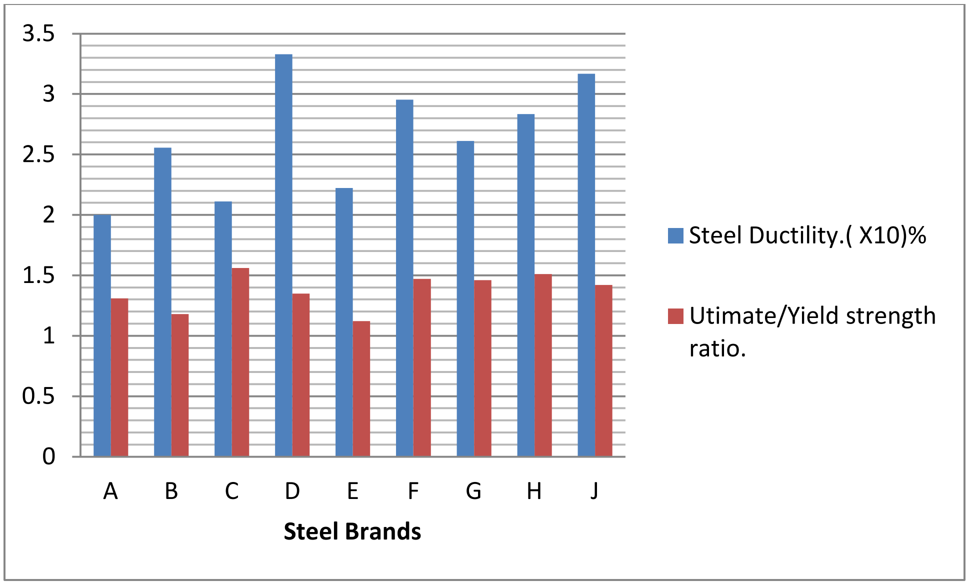


**Figure 2:** Ductility and Ultimate/Yield strength ratio of different steel brands.

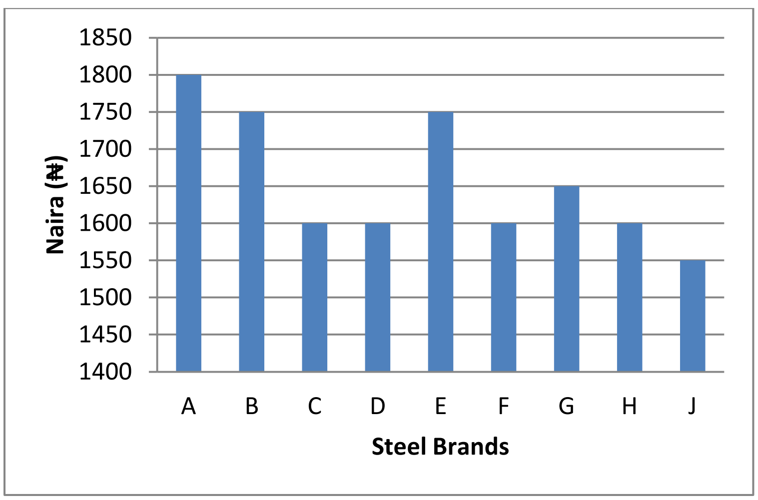


**Figure 3:** Cost of standard length (12m) of the different steel brands.

# CONCLUSIONS.

1. All identified steel brands satisfy its specified diameters if 12mm.

2. By local and foreign standards, only three (3) of the nine (9) identified steel brands meet the required yield strength of between 460-500 MPa as design value in BS 8110:1997 and minimum values in NIS 117:2004 and BS 4449:2005. See Fig. 1.

3. All steel brands satisfy the required minimum percentage elongation of 7.5% as specified in BS4449:2005. As seen in Fig.2, the least elongation is 20%. Prabir *et al* (2004) asserts that the greater the elongation, the better.

4. Four (4) of all identified steel brands satisfy the ultimate to yield strength ratio of between 1.15-1.35 while the rest of the brands are greater than 1.35 as seen in Fig. 2. Almost all brands that meet this requirement also met the yield strength requirement.

5. All steel brands that falls short of strength requirements are relatively cheaper than the ones that met the standard as seen in Fig. 3. They also didn't meet the ultimate to yield strength ratio of 1.15-1.35 as specified in BS4449:2005.

6. Conclusion No. five (5) above tend to agree with BS4449:2005 that a relationship exist between the ultimate/yield strengths and their ratios that confirm a good quality steel. Since the best steel brands that satisfy the ultimate to yield strength ratio range also satisfies the strength requirement.

7. The steel marketers admit that though the standard length is 12m (40ft), it's usually less but always greater than 38ft.

## RECOMMENDATIONS.

1. It is highly recommended that all steel batches be randomly sampled and tested to ensure compliance before being used in construction work.

2. Standard regulatory agencies within the country should undertake periodic market survey to identify substandard product and discipline erring brands.

3. In calculating accurately the number of reinforcements needed for a project by Quantity Surveyors (QS), it is recommended on the interim that lengths be based on market dimension of 38ft and not the usual 40ft pending when regulatory authorities are able to enforce compliance on the manufacturers to produce 40ft standard bars for proper on-site steel scheduling.

4. Nigerian Structural design Engineers should either base their designs on 340 MPa or use greater factors of safety when designing for structures in rural areas that have restricted access to laboratories to ameliorate the effects of these margins from the standard strength.

5. Building contractors should be careful with cheap reinforcements and other practices that seems to "reduce cost", these mostly results in the purchase of sub-standard steel materials as shown in Fig.3 that the cheaper ones are substandard bars.

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# ABOVE AND BEYOND: ACCESS TECHNIQUES FOR THE ASSESSMENT OF BUILDINGS AND STRUCTURES

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## ABSTRACT

There are many reasons that architects, engineers, contractors, and others may require access to the exterior of a building or to the underside of a bridge structure. Often times suspended scaffolding, supported scaffolding, mast climbers, aerial work platforms, or snooper trucks provide access adequate to perform the necessary tasks. Occasionally, conditions are encountered where the use of traditional means of access is not feasible or economical. Under such conditions, the use of rope access techniques can provide an efficient alternative.

This paper will present the advantages and disadvantages of each of these systems and describe how utilizing rope access can provide access to areas many would think inaccessible, or at least extremely difficult and costly to access.

What is rope access? What is required to be certified to perform this work? What is the Society of Professional Rope Access Technicians (SPRAT)? What types of structures can you access from ropes? These questions will be answered and the following case studies presented: the Washington Monument in Washington, D.C.; the Bridge of the Americas in Panama City, Panama; the Bank of America Building in Providence, Rhode Island; and others to demonstrate the capabilities rope access can provide and how incorporating rope access into survey, inspection, and repair programs may better serve the Client.

## KEYWORDS

Safety
Inspection
Building Envelope
Elevation
Bridge Inspection
Natural Disasters

## REASONS FOR ACCESS

Maintenance of buildings and other structures is reliant upon access. While many of the elements may be easily accessible or within a person's reach, other elements require access via special aerial work platforms, scaffolds, or other less common means. Large building and bridge exteriors are made up of many elements that can only be inspected using specialty access means.

In the case of a commercial building, facility managers work to maintain the air- and water-tightness of the building exterior to maintain the safety and comfort of the occupants within. Any penetrations through the building enclosure are potential sources of air or moisture infiltration. Continuity of sealants, seals, mortar joints, and other elements that participate in the tightness of a building enclosure must be inspected and maintained on a regular basis. When any of these elements are beyond reach using conventional access methods, other means must be implemented. Regular building maintenance may include facade inspections, building enclosure assessments, and structural inspections.

Many cities in the U.S. require periodic facade inspections to confirm safe conditions of buildings over a certain height. Deferred maintenance can lead to potential life safety hazards to pedestrians including broken glass and spalled masonry or concrete. An experienced licensed engineer or architect must certify the building for safety of the public and general water-tightness of the building enclosure. Buildings of a particular height must be inspected up close for at least a portion of the facades, depending on the local governing ordinance.

In the case of most bridges, the local department of transportation is responsible for maintaining bridge safety for the people who travel over and beneath the bridge. These bridges are exposed to weather and live loads regularly. They are also exposed to salts and corrosive materials that may be deposited by cars and other vehicles for snow and ice removal. While the top of the bridge deck can be inspected from the deck, deterioration of the soffit, piers, and other structural elements sometimes requires specialty access. Maintenance of bridges may include routine inspections and special member inspections.

Comfort and safety of users, occupants, or those who come within close proximity of the structure are important. Beyond the need for routine maintenance, structures must also be accessed to address reports of water leakage, structural damage, or material deterioration; air and moisture leaks can make an office uninhabitable while spalling stone and concrete can pose a safety hazard to the people below. Building enclosure investigations, including water leakage testing, inspection openings, and non-destructive evaluation techniques, are among the services that can require special access.

# TYPES OF ACCESS

### Supported Scaffolds

According to Occupational Safety and Health Administration (OSHA) (Occupational Safety and Health Administration, 2004), supported scaffolds consist of, "…one or more platforms supported by outrigger beams, brackets, poles, legs, uprights, posts, frames, or similar rigid support." They provide convenient access to structures of height while allowing occupants to move freely along the entire length of the scaffold with no requirement for personal fall protection equipment when guardrail systems are correctly installed (Figure 1). They are capable of supporting large loads and can be used by several trades simultaneously. Supported scaffolds can be arranged in various geometric configurations and require minimal safety training. They are labor intensive to set up and remove as well as require a solid, semi-level surface for installation. Once in place, supported scaffolding typically remains in place for the duration of the project, and cannot be moved or relocated easily.

### Suspended Scaffolds

According to OSHA (Occupational Safety and Health Administration, 2004), suspended scaffolds are, "…platforms suspended by ropes, or other non-rigid means, from an overhead structure." Suspended scaffolds (Figure 2) can provide access to structures of significant height while enabling relatively quick relocations. Suspended scaffolding systems that are permanently installed on buildings, also known as "house rigs," provide highly efficient and effective access since they are designed for a specific structure. Suspended scaffolds can travel vertically at speeds of up to 35 feet per minute and are adaptable to various geometric configurations. Unlike supported scaffolds, suspended scaffolds require less labor to assemble and break down. While providing close range access to most exterior surfaces of the structure, one disadvantage of suspended scaffolds is their limited ability to accommodate large projections, setbacks, or overhangs. Though their live load capacity is generally less than that of a supported scaffold, suspended scaffolds can carry sufficient materials and personnel to perform work efficiently at great heights.

### Aerial Work Platforms

According to OSHA (Occupational Safety and Health Administration, 2004), aerial work platforms are typically vehicle-mounted devices used to elevate personnel (Figure 3). These include extendable boom platforms, aerial ladders, vertical towers, and any combination thereof. Aerial work platforms provide the most direct and efficient means to reach a variety of areas on a structure's exterior. They are relatively inexpensive to rent for brief periods and can be used with minimal set up or removal time. Training is often required to operate aerial work platforms and the site layout can limit where they can be used and stored; jurisdictional use permits (for roadway lane or sidewalk closures) and traffic control details can also be necessary when using an aerial platform. Each lift has a maximum working height that it cannot safely exceed, as well as a limited capacity (both in weight and space) for carrying personnel and materials.

**Mast Climbers**

Mast climbers are an alternate form of powered platform that travels along one or more fixed masts that are attached to a building or structure (Figure 4). They are an efficient means of carrying heavy material and personnel. They can provide discreet access to a portion of a building or structure. Safe use is highly dependent on the integrity of the ground on which it is installed and the wall to which it is attached. Similarly, existing conditions like sidewalk vaults and elevated concrete slabs over interior spaces can limit the use of mast climbers or at least require alterations to the substrate supporting the mast climber vertical loads. When mast climbers are installed with less than one foot distance from the adjacent vertical wall, no fall protection is required. Like other access means, mast climbers require competent users for safe and efficient operation. Mast climbers are one of the more expensive access devices due to the costs to transport, install, and remove them.

**Rope Access**

Rope access provides a means to perform lightweight operations, such as inspections and small material removal, and material sampling. It involves two ropes per worker that are tied back to independent anchor points, each having load capacities of 5,000 pounds (Figure 5 and Figure 6) (Occupational Safety and Health Administration, 2004). The pair of ropes includes one for a working line and one for a safety line. As long as anchors are available, the ropes are relatively quick to setup and take down; they are also easily moved around the jobsite to various facades or roof locations. Rope access has a low operational impact and can be more efficient than other access means on irregular building geometries. Rope access does require considerable training to perform safely and its suitability for projects is limited by the amount of heavy tools and material the rope access personnel can carry.

## ROPE ACCESS CERTIFICATION REQUIREMENTS

Rope access is the use of ropes and specialized hardware to provide access and support to workers. Some of the tasks performed from ropes include sealant installation and surface preparation, sand blasting, pressure washing, concrete repair, painting, rock scaling and anchoring, photography, cinematography, and geological surveys.

There are two primary rope access professional trade organizations that have established rope access qualifications and requirements nationally and internationally. The Industrial Rope Access Trade Association (IRATA) and the Society of Professional Rope Access Technicians (SPRAT) provide standards for certification of rope access personnel.

"SPRAT supports companies and technicians using rope access with certification programs, regulatory support, networking, and opportunities to participate in developing industry-consensus standards." (Society of Professional Rope Access Technicians, 2007). There are three SPRAT certification levels: Level I (Rope Access Worker), Level II (Rope Access Lead Technician), and Level III (Rope Access Supervisor). As a Level I technician, workers are qualified to work on ropes under supervision of a Level II or

Level III technician and to inspect their own equipment and safety systems. As a Level II technician, workers are qualified to work on ropes under supervision of a Level III technician, to rig more complex access systems, and perform a wider range of rescue techniques. Level III technicians supervise rope access work and are responsible for the safety management of the job.

Each level requires thirty-two hours of training with increasing hours of experience. In addition, technicians must re-certify every three years. Some of the certification skills include identifying jobsite hazards, managing personal safety, setting anchors, inspecting hardware, ascending and descending on ropes, transferring from one set of ropes to another, and rescuing oneself and/or other rope access personnel. The hours required and skills learned during the training and certification process provides the rope access workers the ability to perform rope access under difficult conditions, should they arise. Safety should always be the number one priority.

## IS ROPE ACCESS THE RIGHT CHOICE?

When considering the scope of the inspection or investigation work, professionals must consider if rope access is the right choice for a project. In many instances, rope access may be the only means of accessing an area of a building or structure; however, it may not be feasible if there are no suitable anchor points that are capable of supporting a 5,000 pound ultimate load.

Time constraints and budget limitations increase the appeal of rope access. As compared to the scaffolds and aerial work platforms previously mentioned, ropes are relatively easy to setup and take down. Personnel can access many parts of one building or structure in a day by moving anchor points or redirecting the set of ropes. In addition, Level II and III technicians have been trained and certified to setup their own working ropes, and do not require additional contractor support.

The benefits of rope access are not always clear. The cost of certifying staff, traveling to different locations, and purchasing specialized equipment is often a larger expense than that for other access methods; however, when considering time constraints for a particular job and the person-hours necessary to complete an inspection, rope access is often comparable or more cost-efficient. Other access methods can require more time for mobilization, movement, and demobilization of the access means.

Rope access personnel can carry light hand tools with them for inspection and light construction activities; however, heavy construction may necessitate use of larger tools that are suspended from independent lines.

## CASE STUDIES

Wiss, Janney, Elstner Associates, Inc. (WJE) has performed inspections and investigations via rope access on buildings and structures nationally and internationally. Some of the more recent endeavors include the Washington Monument, the Washington National Cathedral, the Bridge of the Americas over the Panama Canal, the Chicago Tribune Tower, and the Bank of America Building in Providence, RI.

**The Washington Monument**

As the world's tallest all-masonry structure, the Washington Monument stands at 555 feet 5-1/8-inches (Figure 7). The original design by Robert Mills was selected in 1845 and begun in 1848. Construction was halted at 156 feet when funding ran out in 1854. Following the American Civil War and the Nation's Centennial in 1876, the National Government took ownership and transferred construction to the Army Corps of Engineers. Lt. Col. Thomas Lincoln Casey headed up the study under the Army Corps and revised the design to that of the present day structure. In order to continue construction, additional foundation support was added and the upper six feet of the shaft was removed. Lt. Casey also developed a steam hoist that aided in construction of the remaining 400 feet.

The Monument was accessed as part of an assessment following the August 23, 2011 5.8 Mw earthquake centered near Mineral, Virginia. Rope access was the preferred method of access to perform a close-range inspection as it was more cost-effective and time-efficient than supported scaffold and could provide access to the pyramidion, which suspended scaffold access could not provide. Rope access technicians rappelled each of the four faces to document conditions and remove loose material. The anchors for the drops were secured to interior marble units and redirected on continuous slings secured around the top of the pyramidion. The rope access technicians accessed the ropes through the small windows located on each of the four facades at the observation level. During the survey, loose material was removed and all observed distress was documented using iPads, enabling comparison with the conditions documented during the 1999 restoration work.

In addition to the small windows, there were several challenges associated with this inspection related to the access. With no projections or surface elements to help with movement and accessing various places on the facade, personnel had to setup a planned and temporary redirection along a continuous tension line at the base of the pyramidion for the various "drops" on the Monument shaft. Redirection is a point which the ropes are tied to another object to re-direct them at a location other than the original anchor locations.

**Washington National Cathedral**

The Washington National Cathedral was formerly known as The Cathedral Church of Saint Peter and Saint Paul in Washington, D.C. (Figure 8). The church is Gothic Revival design and receives nearly 400,000 visitors each year. Its design concept dates back the

Pierre L'Enfant's Plan of the Federal City in 1792. Though construction began in 1907, the final pinnacle was not completed until September 29, 1990.

The Cathedral exterior was accessed using ropes as part of assessment and stabilization efforts following the August 23, 2011 earthquake. Rope access was the preferred method of access to perform a close-range inspection at the west towers as it was the most effective way to quickly evaluate the potential fall hazards over the main entrance in an effort to reopen the Cathedral to the public. Mobilizing a supported scaffold to survey the west towers would likely have taken much longer. Technicians rappelled the Central and two West towers to conduct visual surveys and documented any evidence of distress. In addition, rope access technicians accessed the pinnacles via lead climbing techniques. This particular lead climbing work involved rope access on belay and setting new anchor points while climbing up and around the pinnacles. Anchor points were created around tower limestone units for both types of access. During these surveys, loose material was removed and other deficient conditions were documented using iPads.

The challenges associated with the Cathedral involved the stability of the existing structure elements. Many of these had to be stabilized with cables or removed prior to rope access being performed.

**The Bridge of the Americas**

Completed in 1962, The Bridge of the Americas crosses the Pacific approach to the Panama Canal near Panama City. The bridge is 5,425 feet long with fourteen spans between abutments. For more than forty years, it was a key part of the Pan-American Highway. The bridge is a cantilever design with a tied arch suspended span. The bridge was accessed to facilitate a condition assessment.

Rope access was selected for inspecting the concrete piers for cracking and the bridge truss structure as it provided the most mobility and allowed continued access to the roadway. Specifically, access on the bridge involved rappelling and ascending as well as lead climbing on belay (Figure 9). In order to access the tied arch truss members, rope access technicians were belayed by another technician. While they traversed the members, they created intermediate anchors along the inspection route to reduce the distance of a potential fall.

The Bridge of the Americas is over one mile long and consequently one of the greatest challenges was the distance from land at any given inspection point along the span. If a safety issue had occurred, technicians would have had to rely on their own training, and that of their team members, for rescue as assistance from an outside agency would have taken longer to arrive.

**The Tribune Tower**

The Tribune Tower in Chicago, Illinois was built in 1922 in the neo-Gothic style that popular at the time. This skyscraper was based on the winning submission of over 260 entries for the design of the headquarters of the Chicago Tribune. Completed in 1925, the limestone-clad building is 462 feet tall with ornate flying buttresses at the top of the structure.

The Tribune Tower was accessed to facilitate a recurring facade inspection performed every five years to satisfy the City of Chicago's local facade ordinance. The ropes used to perform drops on the tower were anchored to the limestone buttresses. To access each of the buttresses, rope access technicians rappelled down the tower to the top of the buttresses, traversed across, and then redirected to the top of each of the buttress turrets (Figure 10). Anchors were installed in the turrets years before these facade inspections, which enabled easy redirects.

There were many ornamental elements on the Tribune Tower that had to be considered when performing the access drops that would make other means of access much more time consuming and expensive to design and erect. The locations where the ropes were lowered were often as important as positioning of the technicians' themselves during the drops.

**Bank of America Building**

The Bank of America building in downtown Providence was built in 1927 as the Industrial Trust Tower, designed by New York architects Walker & Gillette. It was designed in the Art Deco style and incorporates several stepped roofs. The building has a history of falling debris, including a decorative "eagle" from the lantern level at the top, which led to the removal of similar units.

WJE was tasked with removing loose limestone fragments, and assessing the overall condition of the facade (Figure 11). Rope access provided an efficient means of looking at each facade on the building from every roof level. Comparing it to the option of using suspended scaffold, the rope access work took only one week to complete with a team of WJE personnel versus eight weeks with contractor assistance on swing stages.

Access to the facade began at the equivalent of the twenty-ninth floor under the lantern level. From there the ropes were either redirected or moved down to the twenty-seventh floor to perform several more drops. There are two main roofs on the twenty-third floor (north and south), at which anchors were established for the rest of the drops. The ropes were then redirected at all of the lower roofs to accomplish the remaining drops. For all anchors, the limestone elements served as the independent anchor points for each rope.

There are nesting Peregrine falcons at the Bank of America building. Peregrine falcons are aggressive, especially when their young are present. Scheduling of the inspections was planned according to when the young birds were gone from the nest so as not to provoke the nesting pair and potentially threaten the safety of the technicians.

## CONCLUSION

Buildings and other structures often require periodic maintenance and sometimes more detailed inspections or repairs. There are many types of access available to the construction industry to satisfy many of these needs; however, there are certain buildings, structures, or procedures that lend themselves to the specific advantages of rope access. Each method of access has its own advantages and disadvantages that must be considered given specific project circumstances set by the owner or the structure itself. These can include cost, the time required for the work activity, anchorage types and availability, or obstacles impeding access.

Supported scaffolds, suspended scaffolds, aerial work platforms, mast climbers, and rope access provide varying levels of capacity for building materials and construction tools as well as ease of access to multiple locations under a variety of job conditions. When construction or inspections will be ongoing for an extended period of time, a means of access that is semi-permanent, has a platform to provide more capacity for materials, and is more efficient for required labor activities. While rope access is generally less comfortable for longer periods of work, it provides greater flexibility in moving to different locations on a structure and enables a large area to be accessed in a short period of time. The job location, surrounding conditions at grade, anchor tie-offs at the roof, owner requirements, and other restrictions will determine the appropriate means of access.

# Figures

*Figure 1. Supported scaffolds*

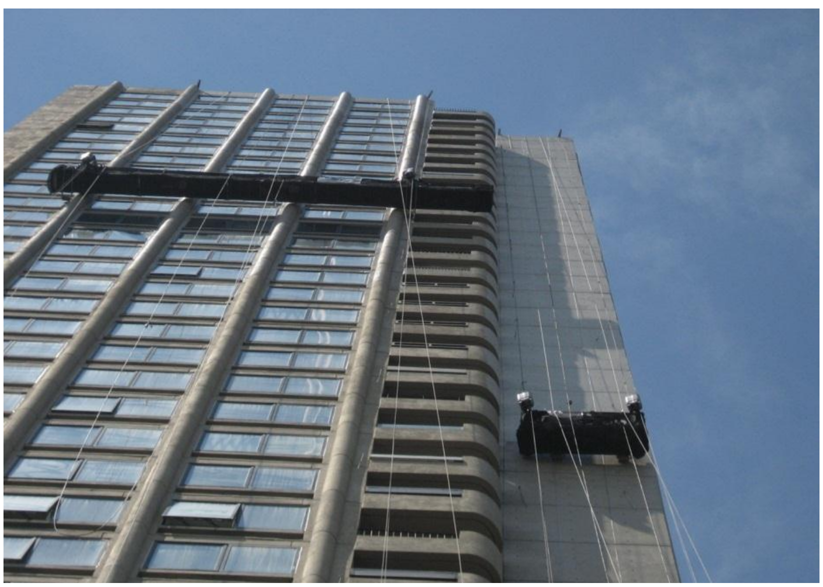

*Figure 2. Suspended scaffolds*

*Figure 3. Aerial work platform*

*Figure 4. Mast climbers*

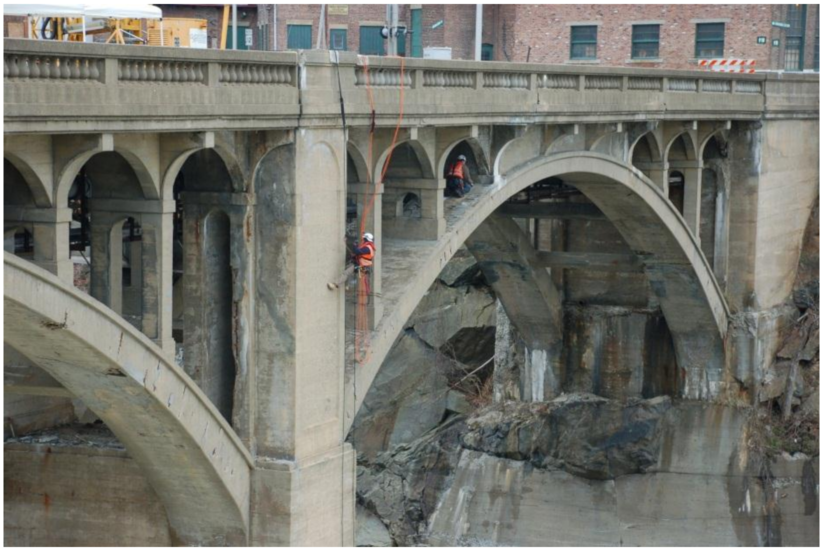

*Figure 5. Rope access*

*Figure 6. Example of rope access*

*Figure 7. Rope access on the Washington Monument*

*Figure 8. Rope access on Washington National Cathedral*

*Figure 9. Rope access on a pier at the Bridge of the Americas*

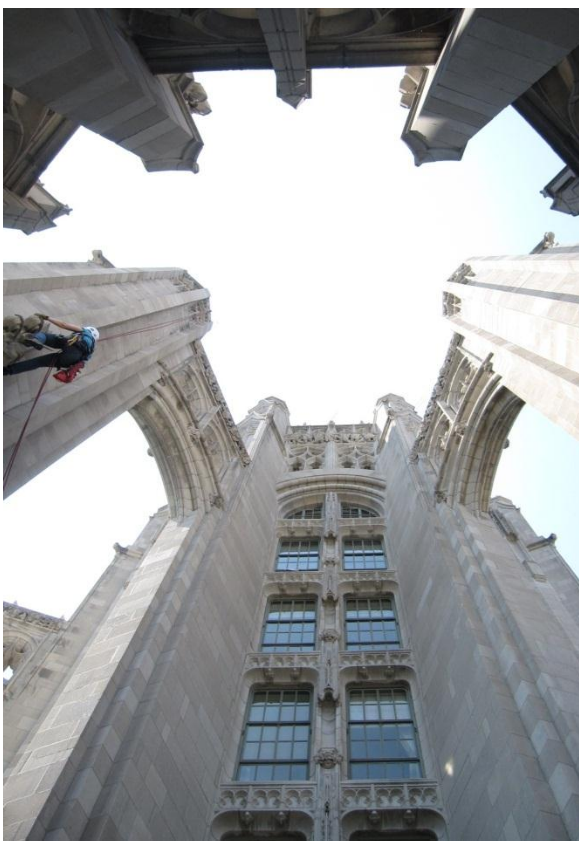

*Figure 10. Rope access on a buttress at the Chicago Tribune Tower*

*Figure 11. Rope access on the Bank of America building*

Occupational Safety and Health Administration, 2004. *www.osha.gov.* [Online] Available at: <http://www.osha.gov> [Accessed 1 October 2012].

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# Exploiting Modern Opportunities in AEC Industry: A Paradigm of Future Opportunities

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***ABSTRACT:*** *This paper focuses on the potential for developing an interactive Virtual Reality (VR) environment that exploits new concepts such as parametric design and genetic algorithm as a method of computational architecture through the conceptual design process. Existing tools and decision support mechanisms are investigated as part of this process. The proposed system introduces the potential of combining different concepts under the chamber of a single VR environment. Influential factors in this area are: form generation, change management, conceptual design illustration, and collaboration throughout the whole design process. First part of this paper introduces the basics of conceptual design, then critically reviews design thinking parallel with the design process; thereafter provides a roadmap for conceptual design and computational support, with a specific focus on the early conceptual design stage (including computational methods for sketching and collaboration throughout conceptual design). Extant literature on the characteristics of collaborative behaviour within the initial conceptual architectural design processes performed through virtual environments are examined. Extant literature highlights the importance of computational design in the Architecture, Engineering, and Construction (AEC) industry. However, there is a significant knowledge gap in literature concerning the veracity of findings to date which explicitly identify the congruent links and support mechanisms needed to overtly exploit the opportunities presented with new computational design methods. This research is the first of the kind to purposefully endeavour to uncover new insight and understanding into virtual generative workspaces, especially though new social interactions and decision-making criteria. Research findings to date have identified new insight into how AEC designers think during the early conceptual design stages. These issues are used to satiate the pivotal drivers, priorities, and critical success factors needed for effective operationalisation through a conceptual design support tool and possible future directions within computational design strategy. The outcomes and intervention of this research will be used to develop a 'proof of concept' prototype to reveal the role of generative design methods integrated into a single dynamic and flexible VR environment which supports early conceptual AEC design process.*

***KEYWORDS:*** *Conceptual design, Virtual Reality, Generative and Parametric design, Sketching, Collaborative design environment, Computer-based environment.*

## 1. Background to the study

Two investigation steps (studying design process individually, and tools that support early design stages) were envisaged to help explore the potential for an interactive VR environment to support the conceptual design process. In this paper, firstly the practical basis of designing is described, followed by the computational support needed for designing - focusing specifically on the early design stages (including computational methods for sketching and collaboration throughout a specific design).

## 1.1 Introduction to design process

> *"The Natural science are concerned with how things are . . . design on the other hand is concerned with how things ought to be* (Simon, 1969)*."*

The process of designing is more developed in some, than others, either through heredity or education (Cross, 2007). Given this, designing can be considered as the process of creating/adopting rules (building codes standards, construction systems standards etc.) and then working within these rules in order to obtain certain objectives (Gross, 1996). There are two primary views about the designing process; first as a process that starts with a certain problem and ends with solution to that problem; and the second view is a process to clarify the problems at the first step in order to solve them later on (Johnson et al., 2009). Thus, computational support for sketching in design can be defined as an "iterative process of problem finding and explore possible solutions within the current conception of the problem” (Johnson et al., 2009).

## 2. Aim and objectives

In order to address the problem statement raised from the literature review, the overarching aim of this research is to identify the potential for a conceptual design tool aid to support the decision-making process during the early stages of design. The possibility of using VR in architectural design has earlier been explored in several projects (Jones, 1992; McCall et al., 1992; Marples, 1960; Gross, 2007). Accordingly, the application of VR in architecture and construction has focused mainly on the use of VR as a visualisation tool and a method of presenting projects with commercial purposes, whereas, regarding the latest technological developments, VR can be integrated with new concepts such as parametric design, genetic algorithms, and BIM. This paper explores methods in which VR is employed not as a representational tool for visualization per se, but as a comprehensive support system for design. The overall goal of this research is enhancement of design process by developing a framework that boost designer’s abilities by evolving surprising and challenging designs and assist the designer throughout the process (change management, modification of the model, and etc.). This paper proposes an uncovered potential for digital design in AEC. The methods introduced are in abstract form and explore on of the many possible potential directions of computational architectural methods.

### 2.1 Literature review methodological approach

This research is purposefully aligned to tease out both the philosophical underpinnings of design theory continuum per se, matched against the practical constructs of research practice (including the technology and tools used to deliver this). This study focused on existing academic literature covering nine core areas. The literature was identified via online search among top ten journals of design and conference proceedings, as well as other research databases and analysed using NVivo. The main subjects were selected based on NVivo’s “Word Frequency Query” amongst selected publications. The minimum length for words in the frequency analysis was set to five and the similarity scale was set to four out of five in order to increase focus and veracity. Figure 1 demonstrates an overview of the NVivo result.


**Figure 1: Word Frequency Analysis**

Such an approach was used to shape, inform, and provide granular data (to help identify the delimiters). Table 1 reveals the core drivers and seminal authors.

**Table 1. Research focus: analysis of core drivers**

| Subjects | Description | Authors |
|---|---|---|
| Design research: Conceptual design and design thinking | The process in which designers collaboratively author an assembly design | (Cross, 2007; Dorst et al., 1995; Maher et al., 1997; Cross, 1999; Cross, 2001; Gross et al., 2007; Landay et al, 1995) |
| Computational support for design | Creating the suitable 3D conceptual design and primitives | (Gross, 1994; Yun et al., 2011; Gross et al., 1995; Leigh et al., 1999; Narahara, 2007; Do et al., 2007; Do et al., 2009; Johnson et al., 2009; Gross, 2009; Bisker et al., 2010) |
| CAD tools | Computer aided design tools | (Whyte et al., 1999; Moum, 2006; Ibrahim et al., 2010; Cheon et al., 2012) |
| Generative design | Using a set of rules or an algorithm in order to generate designs (architectural forms) | (Cera et al., 2002; Narahara, 2007; Baskinger, 2010; Krish S., 2011; Leach, 2009; Kolarevic, 2000; Subbu et al., 1999; McCormack et al., 1999; Mehaffy, 2008; Woodbury, 1991; Laszlo et al., 2002; Singh et al., 2012; Roudavski, 2009; Boden et al., 2009) |
| Parametric Design | Use of parameters to define a form and relations | (Marques et al., 2006; Fischer et al., 2005; Fischer et al., 2003; Matcha, 2007; Butz et al., 2005) |
| BIM | Intelligent model-based process | (Ibrahim 2004; Leeuwis, 2012; Hartmann et al., 2007) |
| Knowledge sharing: collaboration | Collaborative design | (Chengzhi, 1994; Goldschmidt, 1995; Cross et al., 1995; Gross et al., 1998; Cera et al., 2002; Shelbourn et al., 2007; Goulding et al., 2011) |
| Design illustration | Including hand and computational sketching | (Goldschmidt, 1991; Do et al., 2001; Bilda et al., 2005; Gross, 2009) |
| Conceptual design sketching | Drawing made through out early design stages by designer | (Kramer, 1994; Gross, 1996; Citrin et al., 1996; Citrin et al., 1997; Jonson, 2003; Bilda et al., 2006; Ibrahim et al., 2010) |
| Collaborative sketching | Collaborative knowledge annotation for describing shapes | (Gross, 1992; Do et al., 2001; Li-rong Wang et al., 2009; Ibrahim, 2010; Cheon et al., 2012) |
| Tool development | | (Gross, 1987; Gross, 1992; Gross, 1994; Gross, 1996; Gross, 1996; Gross, 1994; Gross et al., 1996; Gross et al., 1996; Gross et al., 2001; Jung et al., 2002; Jung et al., 2002; Johnson et al., 2006; Gross et al., 2007; Gross et al., 2007) |

## 3. The literature review: VR Sketching and collaboration

VR has been defined as a 3D computer-generated alternative environment to be immersed in, for navigating around and interacting with (Briggs, 1996; Pour Rahimian et al., 2008), or as a component of communication taking place in a 'synthetic' space, which embeds human as its integral part (Regenbrecht, 1996; Sampaio et al., 2010). The definitions of VR systems usually includes a computer capable of real-time animation, controlled by a set of wired gloves and a position tracker, and using a head-mounted stereoscopic display as visual output. For instance, Regenbrecht et al. (1996) defined the tangible components of VR as a congruent set of hardware and software, with actors within a three-dimensional or multi-dimensional input/output space, where actors can interact with other autonomous objects, in real time. VR has also been defined as a simulated world, which comprises of some computer-generated images conceived via head mounted eye goggles and wired clothing – thereby enabling end users to interact in a realistic three-dimensional situation (Yoh, 2001). VR tools can be a powerful collaborative design system in founding a common ground for all participants in designing process, and help the designers to employ more intuitive digital design tools in order to synchronise information between design teams. In addition, it helps the designer by providing an environment where their ideas can be better organised, analysed and tested (Heath, 1984). The merits of the VR to the construction industry are being identified, and appreciated by majority of practitioners (Moum, 2006). Moreover, ICT has changed the design process in AEC (Cera et al., 2002). Therefore, communications between different designers in process of designing play a vital role in the success of the project. Moreover, with the current globalisation trend, it is very often that different design stakeholders participate in the design process from different geographical locations (Seng et al., 2005; Wojtowicz, 1994).

### 3.1 VR in AEC

Over the last 30 years, Information and Communications Technology (ICT) systems have matured and enabled construction organisations to fundamentally restructure and enhance their core business functions. Sampaio et al.

(2008) asserted that the main objective of using ICT in construction field is supporting management of digital data, namely to convert, store, protect, process, transmit, and securely retrieve datasets. They acknowledge the commencement of VR techniques as an important stepping stone for data integration in construction design and management as they are capable of holding and presenting the whole information about buildings (e.g. size, material, spatial relationships, mechanical and electrical utilities, and etc.) through a single output. Similarly, Zheng et al. (2009) proposed the use of VR to reduce time and costs in product development and to enhance quality and flexibility for providing continuous computer support during development lifecycle.

Early studies that incorporated VR into the design profession used it as an advanced visualisation medium. Since as early as 1990, VR has been widely used in the AEC industry as it forms a natural medium for building design by providing 3D models, which can be manipulated in real-time and used collaboratively to explore different stages of the construction process (Whyte et al., 1998). It has also been used as a design application to provide collaborative visualisation for improving construction processes (Bouchlaghem et al., 2005). However, expectations of VR have changed during the current decade. For example, Sampaio et al. (2008), asserted that it is increasingly important to incorporate VR 3D visualisation and decision support systems with interactive interfaces in order to perform real-time interactive visual exploration tasks. This thinking supports the position that a collaborative virtual environment is a 3D immersive space in which 3D models are linked to databases, which carry characteristics. This premise has also been followed through other lines of thought, especially in construction planning and management by relating 3D models to time parameters in order to design 4D models (Fischer, 2004), which are controlled through an interactive and multi-access database. In similar studies, 4D VR models have been used to improve many aspects and phases of construction projects by: 1. developing and implementing applications for providing better communication among partners (Leinonen et al., 2003), 2. supporting design creativity (Pour Rahimian et al. 2011), 3. introducing the construction plan to stakeholders (Khanzade et al., 2007), and, 4. following the construction progress (Fischer, 2000).

## 3.2 Diagrammatic representation and reasoning

The process of drawing or sketching is known as a vital activity in the designing process. Design has been benefited from sketching for a long time, certainly before the Renaissance (Cross, 1999). Sketching is considered as an activity that totally controls conceptual design stages, when designers form new ideas. Johnson (Johnson et al. 2009) defined sketching as “the traditional method for early phase design when both problems and solutions are unclear”. Since designers produce more novel and complex objects nowadays the use of sketches has also been improved since that time. Therefore, more advanced drawings are needed and new methods that support designers to produce this kind of drawings are necessary (Cross, 1999). Another important method in conceptual design phases is designers will generate early tentative solutions, but also leave many options open for as long as possible (Schön, 1983). Cross (1999) asserted key aspects of drawing as follows:

- *Using drawings as a communication tool*, so the designer can show to other participants how the design should works or built.
- *“Thinking and reasoning aid”*: by assisting the designer to study many aspects together. Plans, elevations, and details all being drawn, therefore, thought and reasoned at once; also as a catalyst for improvement designer's creativity, like using random sketches in order to explore new concepts; and using drawings to explore, criticise, and discover diverse options.
- *“Generating alternative solutions”* and identifying critical details. The only way that a design problem can be solved is by exploring through a diverse range of solution proposals.
- *Capability to manage various levels of abstraction at the same time.* Sketches help designers to manage their thoughts about the overall concept and details simultaneously.
- “*Storing and retrieving*” Enable designers participate later in the design process to understand the solutions, for what might otherwise be abstruse choices made by earlier designers.
- “*Recall of relevant knowledge”,* so designers can identify applicable information to any possible solution from a huge sources of information.
- *Problem arrangement* throughout solution generation by proceeding the “problem space” and the “solution space” together. Therefore, designers relate problems to their produced solution by using symbols (numbers, texts etc.).
- *Sketching in design reveals solution concept's specifications and properties.*

### 3.3 Importance of collaboration in conceptual architectural design

The quality of the buildings is highly dependent on the early phases of design process of that building (Moum, 2006). A series of design decisions and justification were made by different roles at different stages of a building project; from design to construction. Importance of conceptual design on the next stages of the building process has been studied by several researchers (Johnson et al., 2009; Dorst et al., 1995; Goldschmidt, 1995; Kramer, 1994). The foundation of conceptual design forms as follows: architects generate design solution; in the next step they choose which solutions are good enough to be developed; client(s) decide which design concept (the solutions introduced by the designer) could be the foundation for supplementary improvements, '*through a collaborative decision-making environment'* (among the participants: designer(s), client(s), users, contractors, legislation etc.) (Moum, 2006) (see Figure 1). Therefore, the client's assessment is highly depends on *how designers present their solutions primarily* (Moum, 2006). Based on the aforementioned statement regarding to the importance of collaboration throughout the design process, an effective design tool can be the combination of "*real-world environment*" and "*spatial-experience dimension*" (Moum, 2006). This VR environment can benefit from real time network collaborative technologies and 3D modelling at the same time in order to improve the construction process as well as design process. Hence, this environment should contribute to all the building process, from early design to final stages. To apply such an environment to construction process all the participants (like architects, legislators, contractors, manufacturers etc.) need to access the environment at the same time, so they can contribute to, or obtain data from the model at the same time (in parallel) (Moum, 2006). Therefore, all the participants access to the environment and there are no parallel models and details. Conflict over the disconnected drawings and details, which is one of the main issues in the construction process, can be decreased with this method (Kiviniemi, 2004). Design education as well as the process itself has been conducted the same way for so many years, whereas, technology development has made new more improved opportunities possible in this area.

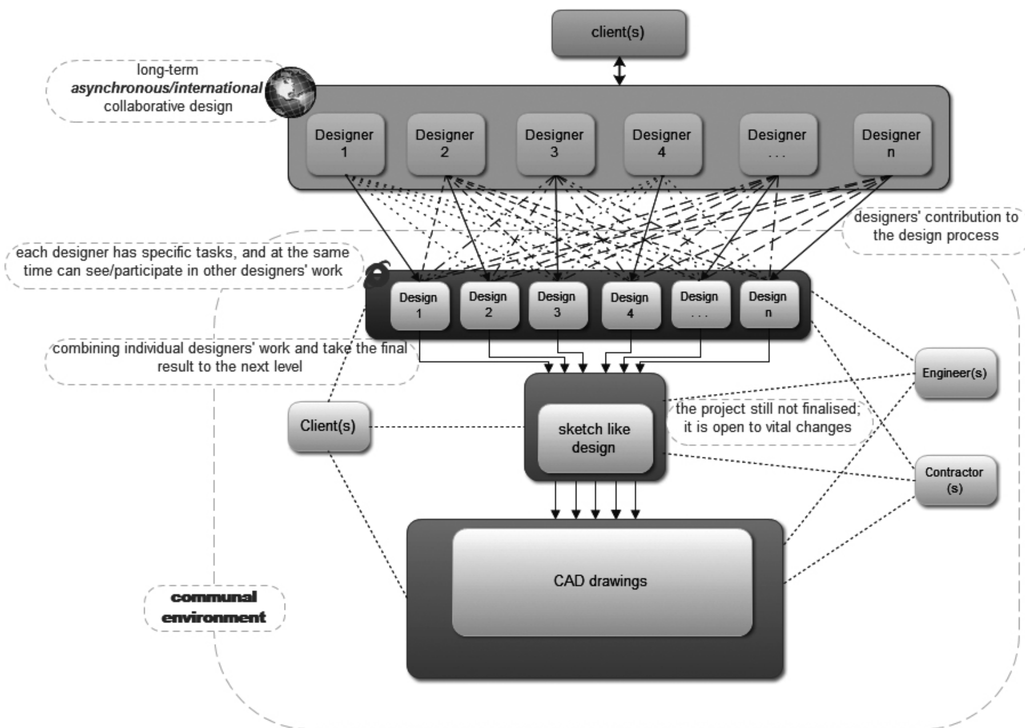


**Figure 2: Collaboration throughout the design process**

## 4. Modern design opportunities

The focus of contemporary AEC design projects is increasingly moving from architecture with aesthetical emphasis towards performance (structure, environment, construction, socioeconomically and cultural, etc.) based architecture (Roudavski, 2009). This shift in design attitude is inviting architecture to adopt new technologies that can support this transition. The AEC designers started adopting technology from industrial design, mechanical engineering and product developments, where performance tends to play a crucial role. These computational design tools are including CATIA, Inventor, Digital Project, SolidWork, Pro Engineer, etc. Moreover, new enhanced computational design methods based on existing methods and concepts such as genetic algorithms, parametric design, isomorphic surfaces, kinematics and dynamics, topological space are also being engaged.

Given these changes and new inertia, the research proposes the potential of a VR design environment integrated with new computational design methods in order to maximise their opportunities. For example, the proposed framework exploits genetic algorithm to generate different alternatives, and throughout the modification of the chosen alternative(s) the system uses parametric algorithm for change management during the late design stages through to construction. Following sections describe these two proposed features in more details.

### 4.1 Generative evolutionary design

Application of evolutionary algorithm is proposed for the generation of design alternatives in the proposed VR environment. It is advocated that this approach could enhance the system's capabilities by allowing the generation of complex forms with various details and layout that would not be possible without using such a system. Several researchers have highlighted the benefits of using evolutionary design (Frazer, 2002; Bentley, 1999; Buelow et al., 2002; Janssen, 2006; Narahara et al., 2006). In addition, architectural design has benefited from the application of generative algorithm by five adopting five different techniques: genetic algorithm, cellular automata, L-systems, swarm intelligence and shape grammars (Janssen, 2004). Indicative examples are presented in Table 3.

The aim behind proposing the idea raised in this research is not to epitomise existing systems and approaches per se, rather, the research endeavour is to optimise the design process by integrating and exploiting different existing approaches. Evolutionary design method uses evolutionary software systems (genetic algorithm) in order to enhance designers' abilities during the design process. Evolutionary design is broadly recognised by parametric evolutionary design and generative evolutionary design (Janssen, 2006).

### 4.2 Parametric evolutionary design

This approach is taken on late design stages in order to find the best solution to the design problem amongst different design alternatives. A basic design concept is established in advance. Thereafter, components parameterised by the designer for further improvement. The system evolves these parameters at the last stage to generative alternative design solutions (Janssen 2006). Some examples of parametric evolutionary systems are Rasheed (1998), Rasheed et al., (1999), Dasgupta et al. (1997), Monks et al. (2000), Obayashi et al. (2000), Caldas (2001), and Sasaki et al. ( 2001). Application of parametric design has been successfully adopted in a number of BIM applications as a change management engine. However parametric systems have evolved into effective drawing tools, but still they are not considered as comprehensive AEC design applications. An example of parametric restriction and change management within a system is the distance of a door from the wall or riser of the stairs to assure furnishing clearance.

## 5. Tools for early design stages

Most of computational design tools for early design stages adopt pen and paper like interface. In addition, new improvement in technology, like computer networking, brought new ways of collaboration into the design process, whereas, current methods of collaboration within the design process have been synchronous (same-time), these improvements have made asynchronous (different times) and international collaboration possible in design process (Gross et al., 1998). In addition, technological improvements extend designers capabilities even in synchronous collaborative design. For instance computers are capable of simultaneous work, constraint checking, finding and indexing etc. (Gross et al., 1998). Meetings are traditionally taking place around a conference table, whereas, nowadays the collaboration between design team members, that are geographically dispersed, is possible (Gross et al., 1998).

### 5.1 Tools specification

In architectural design process, many different systems with different design characteristics are being used by different team members. Therefore, each designer is in charge of a specific part, like heating and ventilation, partitions, electricity etc. (Gross et al., 1998). In CAD system, layouts are done separately, in different layers, and then combined together. Therefore, conflicts and problems are postponed until the last phases of design process

and corrections are likely to be ad hoc (Gross et al., 1998) (Figure 1).
Sketching and drawing are *"primary mediums in many design domains"*; a comprehensive design tool should support both *"construction of the artefact and argument about the artefact"* (Gross et al., 1998). "Design tools should assist design teams as well as manage and work within explicit agreement about the design" (Gross et al., 1998). Ideally, such a system should recognise (or have different options or environments) for each stage in early designing process (support working from abstraction to specific details) (Gross, 1996):

- ***Conceptual diagram***: consists of a wide range of design proposals that are equally considered as solutions and compared without commitment (nature of early design phases).
- ***Schematic drawing***: The schematic drawings will typically contain many of the same element and relations in the original diagram (Gross, 1996a), therefore, more details and the designer is more committed.
- ***Final drawings***: the design artefact would be specified for construction with a little room for ambiguity.

A computational support for early design phases needs to allow designer to work "*initially with unidentified forms and configurations and gradually identify them as design progresses toward the schematic and final drawings phases* (Gross, 1996)." This system can be a combination of a tool that emulate pen and paper and highly structured CAD programme (Gross, 1996).

## 5.2 Needs analysis: Existing tools

Design support tools assist designing with two different methods; one look at design as "a linear process beginning with a specific problem and ending with a specific solution", whereas another method is usually define the problem firstly, and then propose solutions for that problem (sketch-based design systems). Recent conceptual design tools are mostly developed versions of previous researches in this area, started about 50 years ago such as Sketchpad (Sutherland, 1963) and GRAIL (Ellis et al., 1969) worked with the support of physical devices like Stylator introduced in 1957 and RAND's tablet developed in 1964 (Johnson et al., 2009).

**Table 2 Common features for computational support systems for sketching**

| Features | Description |
|---|---|
| Easy to use intuitive interface | they can provide user with a natural sketching experience |
| Variety of tools | such as: various brush types and colours, pencils, pens, markers, and airbrushes |
| Layers | help designers to organise their sketches |
| Apply constraints | like make lines parallel |
| Shape enhancement | assists the designer to draw straight lines, circles, ellipses etc. without explicitly entering a mode |
| Pan and zoom | with high quality results, so designer can produce more detailed sketches |
| Post image improvement | by adjusting contrast, colours, size, crop etc. |
| Text support | comments |
| Import and export | allow designer to bring and take the design through different design stages |

## 5.3 Common problems and challenges

Recent developments in computational design have substantially changed conventional design process, therefore, designers' way of working. "This new paradigm aims to locate architectural discourse within a more objective framework when efficient use of resources supersedes the aesthetic indulgence of works" (Leach, 2009).

Many of the available systems (presented in Table 3) are capable of handling complex design processes that vary in overall organisation and configuration by the designer. However, none of these systems are fully capable of purposefully manipulating conceptual design. In order to overcome this barrier, this research proposes a system which exploits and combines new concepts in a single VR environment. The aforementioned system uses genetic algorithm for conceptual design and form generation (population of alternatives); also benefits from advanced features of VR environment for illustration and collaboration in which coupling parametric algorithm for change management.

Moreover, another problem with the aforementioned tools relates to collaboration throughout early design stages, for instance Autodesk® SketchBook support for collaboration and communication is to let the designer "instantly e-mail sketches and annotations", whereas, comprehensive computer tools for design should provide integrated support for both "construction of solution form" and "argumentation about construction" (McCall et al., 1992). A comprehensive set of challenges for developing sketch-based tools are introduced by Johnson (Johnson et al., 2009) as: Traditional sketching, Physical devices support pen-based interaction, Sketch recognition, Human-computer interaction.

**Table 3 Developed tools**

| | Specifications | Tools |
|---|---|---|
| **Non-commercial systems** | | |
| Constraint-based representation | System maintains the constraints and the integrity of the design | SketchPad (Sutherland, 1963); The Sketcher (Medjdoub, 1999); CoDraw (Gross, 1992); BRIAR (Gleicher et al., 1991); |
| Associative representations | Design relations constitute dependencies that are defined by the structure of the underlying model | ReDraw (Kolarevic, 1993) |
| Design grammar representations | Designs are represented by means of a vocabulary of shapes, (defined by lines and labels) and a set of production rules; design relations as well as design transformations are encapsulated in those rules. | Discoverform (Carlson et al., 1990) |
| Hybrid representations | Combination of different representation models | SEED-Layout (Flemming et al., 1995); Floor Layout and Massing Study Programs (Harada, 1998); Performance Simulation Interface (Suter, 2000) |
| **Commercial systems** | Industry-standard CAD systems | Revit (AutoDesk); GenerativeComponents (Bentley systems) |

## 5.4 VR interactive learning environment

The main aim of a VR environment is to provide "a flexible interactive learning environment" for novice designers. This can help novice designers to learn a smart environment that applies real design restrictions and rules to the design process automatically. The level of these restrictions can be amended, so that novice designers can learn how to apply real design restrictions in a gradual way.

# 6. Discussion

Having a single, flexible, and dynamic 3D environment which covers a wide range of architectural design requirements through the design process (early design to construction stage) is a vital necessity for designers. The generative evolutionary design assists the designer(s) through the early design stages, while the VR environment's parametric capabilities provides a direct relation to physical production process (construction). This research presents a valuable set of rubrics for discussion in order to support the early design process, specially:

- Creation of models with relevant links to all required information and details for the development process.
- Creating a generative process capable of controlling the variability of design outcomes, and generation of designs with required level of complexity. Moreover, generate alternatives that differ significantly in terms of overall organisation and configuration.
- Creating an innovative collaborative environment which enables designers to communicate in an efficient way through conceptual design phases (enable both short-term asynchrony and long-term asynchrony).
- Creating a VR environment that support sketches (either by scanning hand-made sketches or by drawing-on-tablet technology) in both 2D and 3D environment.
- Enable designers to edit, save, and improve sketches and designs in a communal environment, hence, all designers (from different geographical regions) can contribute towards the design process.
- Enable designers to take their sketches (2D and/or 3D) to the next levels in order to shape their thoughts and guide it to the final phases gradually.

## 6.1 Overall performance

The proposed system enhances VR environment for both generating and visualising forms. Evolutionary system is developed that is fully integrated in the VR environment. The system will be developed using a programming language embedded in Revit, therefore, allowing the generative process to make direct use of the Revit modelling functions. Moreover, Revit will also be used for visualisation, with all feedback from the evolutionary process being displayed in the Revit interface. There are evolutionary systems developed by Frazer using AutoCAD and Sun's systems integrated with Micro Station. By integrating the evolutionary system with and advanced BIM or CAD modelling application, the generative process in the developmental step can make use of complex geometric functions on the BIM application. Figure 3 reveals the overall performance of the system.

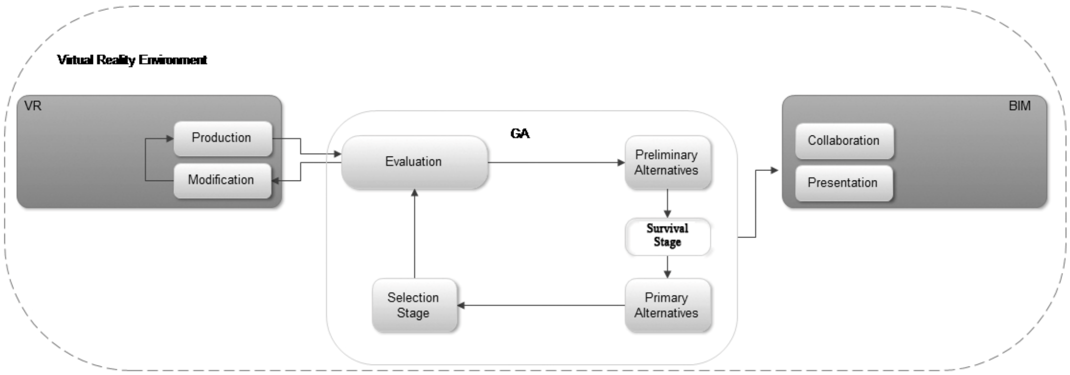


**Figure 3: System overall performance**

## 6.2 Challenges and opportunities

In order to explore the potential for one possible future direction of computational design strategy, general aspects of what our contemporary practice in architecture is facing is discussed. The following is some potential opportunities raised from the literature:

1. Collaboration in design: New technologies and systems such as computer networking, video and computation integration etc. has made new and more advanced opportunities for synchronous and asynchronous collaborative design (SCD and ASCD).
2. Sketch-pad systems: computational support for sketching.
3. Integrating computational sketching systems into Augmented Reality architectural form: Combining sketch-pad tools with real time three-dimension environmental information of the site would help the designers to have a better understanding of how their designs would be in real site, from the early design stages. This could be extended, so the design support environment elaborates more detailed information such as temperature, brightness, humidity, wind direction and sound from early design stages.
4. Digital mock-ups (3D Sketching): Three-dimensional sculpture like interface as a replacement for early design mock-ups.

Given the challenges identified, it is advocated that tools that proactively support and underpin the intrinsic skills needed for effective early design are evaluated through 'objective' measures in order to provide further insight.

## 7. Conclusion

A dynamic and flexible VR environment which covers AEC design requirements, from early stages of design up to the construction process is a vital necessity. Another critical aspect is supporting recent (computational) design paradigms, including generative and parametric design, and BIM. Such A VR environment is capable of providing techniques for exploring and generating design solutions. The proposed VR environment focuses on analysis and optimisation of design solutions for problems at the stage of conceptual design.

This paper critically reviewed seminal literature on ICT tools within the AEC sector in order to highlight the existing theoretical and technical gaps between implementing immersive interactive interfaces that combine support for both design and collaboration. Implementation of such interfaces could lead to new approaches using game-like immersive educational interfaces with the potential to benefit and help actors experience real-world problems in a risk free virtual environment. This is proposed that the next generation of design interfaces should be developed on a database (object-oriented) approach for modelling, with the API augmented to extol the benefits of shared working (through enhanced collaborative environments). The implementation of such approach could leverage significant benefits (e.g. Thai et al., 2009; ACS, 2009; Apple Inc., 2009; and Wellings and Levine, 2010), not least improves users' engagement in the process. Whilst several systems are now being promoted in the marketplace (e.g. Cisco, 2012; Autodesk, 2012; Bentley, 2012), the use and propensity of these have yet to reach maturity. However, further development (with a construction focus) could lead to the emergence of truly immersive environments. Moreover, the concatenation of a Game-Like immersive VR interface could offer global AEC design projects further enhanced opportunities.

Development of this research has presented and outlined a conceptual framework for exploitation of new concepts in computational design and architecture. Future work will concentrate on capturing rubrics and parameters, in order to shape the rubrics of this model, then to develop it further.

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# PARAMETRIC DESIGN PROCEDURES: A NEW APPROACH TO GENERATIVE-FORM IN THE CONCEPTUAL DESIGN PHASE.

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## ABSTRACT

The conceptual design stage often involves a compound set of objectives and constrains such as abstract notions of function and aesthetic, performance, project requirements, site constrains and construction costs. To respond to these complexities, a number of design instances and alternatives need to be developed and assessed against predefined criteria. While this process requires human imagination, computational generative systems are increasingly being used in this stage of the design process. However, some of these approaches have limitations in the ability to make modifications within an interactive environment, requiring a model to be recreated with different attributes and parameters if changing geometry configuration or topology are needed. This research introduces a new approach – Parametric Design Procedures (PDPs) – which combines the techniques of Design Procedures and Parametric Modeling to address the limitations of existing systems. PDPs offer possibilities to explore a particular design instance after a model is constrained through the generation of an infinite number of design instances which can be considered in the evolution of parametric design instances. The rational for, and features of PDPs are described. The viability of this approach is explored through a prototype implementation in Grasshopper. The brief for an architectural design competition is used as the basis for the prototype development. The paper concludes with suggestions for further research and development, for example in the use of other software and other design phases to test the implementation and viability of PDPs.

***Keywords***: conceptual architectural design, generative systems, parametric design procedures,

## INTRODUCTION

The term conceptual architecture is used to characterize a particular design or process that uses conceptualism in architectural design. It is an abstraction that filters unnecessary details and simplifies the object while elements of components and relations among them are determined. The representations at this stage should support various interpretations of design elements while simultaneously allowing them to be adjusted through the use of multiple methods (Emdanat, 1998).

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Basically conceptual design is considered as a challenging stage of the design process in which architects often face a compound set of objectives and constrains. These include abstract notions of function and aesthetic, ecological performance, project requirements and construction cost. Some of the requirements of the conceptual design phase are:

- Generate and explore a huge number of possible design solutions,
- Test and evaluate generated solutions based on predefined criteria,
- Overcome human mental imaginary restrictions,
- Create imaginative forms and creative ideas
- Productivity with less time consuming.

To resolve these complexities, a number of alternatives need to be generated and tested against predefined criteria in order to select the most appropriate option(s) for further design development (Gane and Haymaker, 2007). While this process always requires human imagination, computational generative systems are increasingly being used in this stage of the design process. Such systems include: Transformations of Shape Grammars, Algorithmic design and parametric generative-design. However, all these systems have advantages and limitations regarding generative capabilities, support for complex design and system control by designers. The advantages include the development of satisfactory enhancement of parametric modeling. The limitations however, include the inability to respond to the needs, difficulties of the conceptual design stage, and the requirements for parametric modeling.

This paper reports research that was aimed at demonstrating parametric design procedures as an emergent computational methodology to form generation, complex form finding and formal explorations in the conceptual design phase. This approach was assessed based on the requirements of the conceptual design stage as well as the goals of parametric modeling. The specific objectives of the research were:

- To define needs and difficulties of the conceptual design phase.
- To define goals and objectives of parametric modeling.
- To review current approaches and identify problems as well as limitations.
- To develop an application that demonstrates the use of this technique.
- To assess and validate the capability of PDPs based on defined above needs and goals

The rest of the paper includes a literature review to determine needs and problems of the conceptual design phase and to define the goals and objectives of parametric modeling. Current approaches of generative systems and recent attempts to resolve the limitations of parametric modeling as also reviewed. The concept of PDPs is defined and its application demonstrated through a prototype application using Grasshopper. The paper concludes with a discussion of the findings and recommendations for further research.

## GENERATIVE DESIGN SYSTEMS AND PARAMETRIC DESIGN

In their paper on interactive generative systems, Eckert et al. (1999) argue that generative systems can be considered as an artificial intelligence aid to support humans in achieving creativity especially when such systems are used in an interactive way with designers.

Generative design can generate forms automatically; therefore, designers can generate a huge number of design solutions and explore them in such huge design space within a minimum time as well as evaluate their performance based on a predefined framework. Consequently, generative design will become an evolution of exploring forms which is dramatically essential in the conceptual design phase. There are several methodologies that provide generative designs such as Genetic Algorithms, Shape Grammar and Parametric Techniques. D'Arcy Thompson (Thompson, 1961) in his book 'On Growth and Form' discusses the study of form which can be descriptive or analytical. The method of Cartesian transformations originated from the method of Co-ordinates which was previously used as way to translate the form of a curve into numbers and then into words. Thompson's concept on the study of forms lies in the comparison of related forms instead of a mathematical definition of each deformation. He thought that a form can be better understood by observing it as a deformation of another form, thus two forms can be compared by Cartesian net; this provides a visual framework for the morphologists to understand the relations between forms and transformations as they occur (Figure 1).

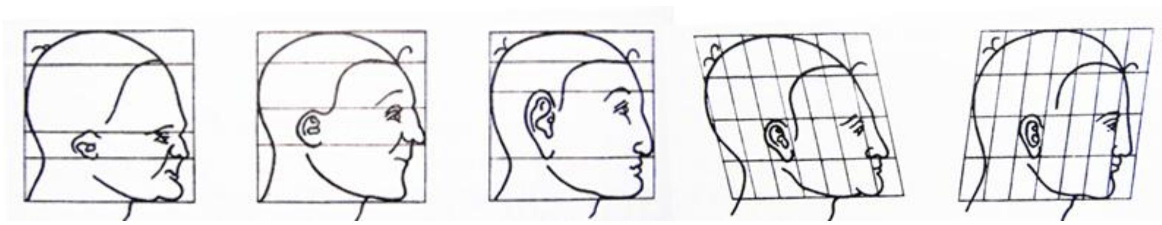

Figure (1): Variations generated using co-ordinates method of Cartesian Transformations (Source: Thompson, 1961).

Transformations of shape grammars are also generative techniques which were originally invented more than three decades ago by Stiny and Gips. Shape Grammars are shapes, computation and languages of design; they are also considered as one of the earliest algorithmic tools in which design can be created and understood directly via computations with shapes instead of indirectly via computation with symbols and text (Stiny, 1976). According to Terry Knight (Knight, 2000), "*a shape grammar is a set of shape rules that apply in a step-by-step way to generate a set, or language, of designs. Shape grammars are both descriptive and generative. The rules of a shape grammar generate or compute designs, and the rules themselves are descriptions of the forms of the generated designs*." The computations start with an initial shape and then applied rules onto the initial shape creates a new design. However, shape grammars look deterministic in restricting rules, thus generated instances might be predictable. It also does not allow transformations at the level of geometry and topology, to generate totally different design solutions.

Originating in other design related fields such as product design, aerospace and automotive design, parametric design has become prevalent in the Architecture, Engineering and Construction (AEC) industries, and architects have implemented parametric design in architectural design (Eastman et al., 2011). Parametric design is also called "associative geometry" (Burry and Murray, 1997 cited in Minh, 2009, p. 1), "Variational design, constraint based design or relational modeling" (Monedero, 1998, p. 158) controlled by parameters and constrains via assembly of associative operations.

When architects alter parametric values to explore various alternative solutions for a particular problem, the model will respond to modifications through automatically updating itself without deleting or remodeling any elements (Stavric and Marina, 2011). According to Burry and Murray (1997, p.1) “parametric modeling software is invaluable for both preliminary and developed design where there is a need for the definition, manipulation and visualization of complex geometry”. Some of the most significant goals of parametric modeling are: flexibility; adaptability; modification without the need to delete or remodel; providing solution spaces to be explored; less time consuming; quick in responding to changes and updating of the whole model; and working with the historical based system where designers can come back at any stages.

On the other hand, parametric modeling only allows variations, which allow the generation of related forms within the same family of forms; it does not allow topological and geometrical transformations to generate an infinite number of design solutions. It is also limited in its flexibility to allow the generation of sophisticated forms and curvilinear surfaces. The development of *‘Design Procedures’* has been proposed to overcome some of the limitations of parametric modeling. However, this approach also has limitations, such as restricting some kind of transformations. Furthermore, the need for scripting knowledge to more fully exploit the benefits of design procedures is usually beyond the designers (architects) who are involved in the conceptual design phase. Design procedures must also be designed to solve a specific problem, for example, the generating columns of the Sagrada Familia church, rod symmetry and twisted towers (Barrios, 2006). As Barrios (2005, p. 25) observes, “…design can be described as a step by step process, where some things can occur over and over again. This can be interpreted as a procedural way of making design.” This suggests that design procedures is a step by step process to be followed and it is a kind of generative system which the designer does not have full control over; the events and the design process should be flexible so that designers can start from anywhere or any step and come back to previous steps when needed. These problems make such approaches less viable to more fully address the needs of designers in the conceptual design phase. All of the reviewed methodologies are attempts to provide architects with a flexible and powerful environment. The development of a new approach which combines the advantages of various approaches is therefore a viable way forward.

## PARAMETRIC DESIGN PROCEDURES (PDPs)

The nature and complexity of the conceptual design stage as well as the demand to generate various design solutions within the same model without the need for programming knowledge led to the idea of incorporating Parametric Design (PD) with Design Procedures (DP) and other significant generative methodologies to introduce a new approach in the name of Parametric Design Procedures (PDPs). This incorporation can be seen as taking viable aspects of PD and DP to overcome the limitations of parametric modeling and DP. PDPs use parameters (e.g. initial shapes, variables, operations, numbers and relationships) as inputs, and calculate them through an encapsulated mathematical process to interactively generate and explore solutions for the design problem. Lecky-Thompson (2006) defines a procedure as "*a named block of code, like a subroutine, but with some additional features. For example, it can accept parameters, which might be input, output, or pass-through*." PDPs use encapsulated codes in the form of visual features without the need to use scripts. Unlike DP, which only supports generative forms which are designed for, PDPs support all kind of designs which means that a parameterized model can be used for many formal explorations. In spite of using initial shapes as parameters, in PDPs shapes have the 2D and 3D transformation capability of other shapes, including non-closed shapes 'which is a condition in Design Procedures that shapes must be closed'. This addresses topological and geometrical transformation limitations of PD and DP. Architects can also switch between operations such as extrusion, rotation, scaling, twisting, etc. to generate completely different instances within the same model, and explore more options – an essential requirement of the conceptual design phase. PDPs works with a historical based platform, and a designer can come back to any particular step to do further modifications. Moreover, Architects have the entire control over the generation procedures thus the generation procedure will allow the combination of automated and non-automation computational procedures. In other words, design instances can be generated interactively via altering parametric values from the beginning to the end of the design process. This approach supports the generation of all kinds of non-Euclidean forms and curvilinear surfaces, which are needed for architectural design in this digital age. Although, the PDPs approach is a computation methodology, the conceptual design process usually starts with some initial steps which are rather manually performed. These include the identification of problems and goals, and initial sketching of 2D shapes and 3D forms which can be moved into a digital environment using the PDPs approach to generate and explore forms. In this context, these constrains can be considered as inputs to the computational framework. Figure (2) shows the system of PDPs as a computational methodology to form generation.

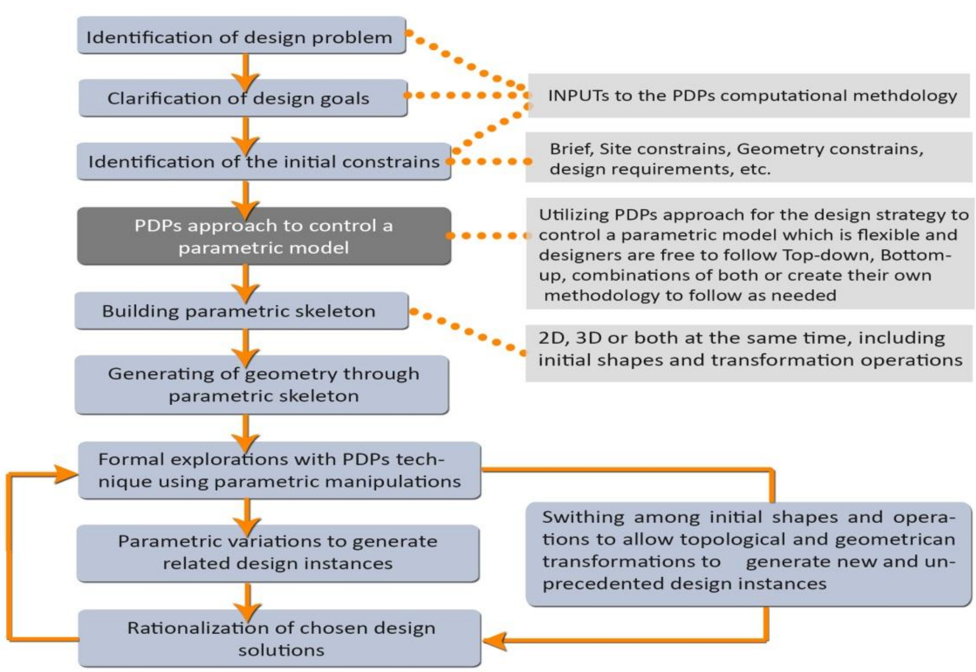


Figure (2): System of PDPs as a computational methodology to generative-forms of the conceptual design.

## RESEARCH METHODOLOGY

The aim of this research was to explore the extent to which parametric design procedures (PDPs) can be used as a computational methodology to generative form in the conceptual design stage. The specific questions were:

- How can PDPs be used as a computational design generative system?
- How can PDPs allow designers to formalize and generate solution spaces that can be explored?

To answer the research questions an application was developed and evaluated with respect to the needs and goals of the conceptual design stage and parametric modeling. Grasshopper 3D was chosen as the software to design and develop the application of PDPs. This was because currently there is no suitable software like Grasshopper to support the PDPs approach. To ensure that the evaluation reflected a realistic scenario with respect to site, aesthetic and other criteria, the brief (program) for architectural competition (*USA: The 2nd Annual International Student Tall Building Design Competition)* was selected as the context. Furthermore, a real site context was selected to design and locate the competition on. The use of self-evaluation in the testing of the application has its limitations, but it was not possible during the timeframe of the research to involve other specialists in the validation process. However, the process adopted has yielded useful insights into the potential benefits of PDPs.

## IMPLEMENTATION OF PDPs USING GRASSHOPPER

The competition brief required imaginative ideas which basically need formal explorations. The goals of this project was to design a tower which could be used as a multipurpose building considering aesthetic, flexibility, adaptability, technology, imaginative ideas, materials and digital revolution. Therefore it was necessary to generate and explore forms to respond to these requirements. For the chosen site context there are basically some geometrical constrains including the built area of tower which could be constrained between 225-625$m^2$, and number of floors and the height of the tower are constrained between 20-50 floors (70-175m height), height of each floor is constrained between 3-4m. Within these constrains the values can be parametrically manipulated later. The work started with thinking about initial shapes, 3D forms and concepts considering the site context and brief requirements. The initial concepts are used as inputs to the computational generative steps in the PDPs system. Computational works start with choosing Grasshopper software (*Grasshopper is a visual programming language originally developed by David Rutten at Robert McNeel & Associates*) and the setting up of parametric values with initial shapes, operations which are parametrically controlled and can be switched to any other shapes or operations (within the same model and definition) when searching for various alternatives. Figure (3) shows generated initial shapes with 2D transformations on the level of topological and geometrical using the same model without remodeling or deletion. The generating process is very easy and quick so that designers generate infinite numbers of design solutions in very short time. Moreover, the designed Grasshopper definition can be easily used to generate forms of other projects which mean the designer becomes a half programmer at the same time.

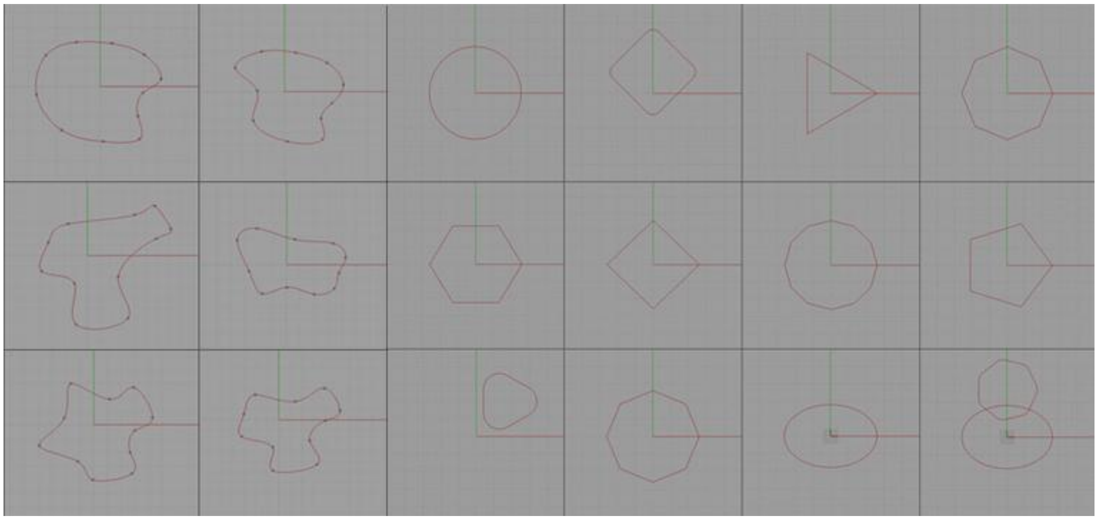

Figure (3): Parameterized values and generated initial shapes using the same model.

Figure (3) shows the capability of PDPs in switching from one shape to another, including any type of curves (e.g. NURBS curves, Polylines etc.), and also allowing closed non-closed to be processed. The shape can be controlled based on plane coordination so that the whole model can be easily moved around. The next step is setting up parametric skeleton, which are fully controlled parametrically. Here we can get flexible initial shapes, number of floors, height of floors and the whole building with all other parametric features including values and operations. The skeletons are generated within the same model and can be used to generate forms at a later time.

After building a geometry on the skeleton, other design instances can be generated via variations, and changing the entire configurations of the model, which is required in the conceptual design phase to assess as many solutions as possible. The design instances in Figure (4) show the capability of PDPs in generating various design instances within the same parameterized model without any deletion through switching among different initial shapes and operations which allow topological and geometrical transformations.

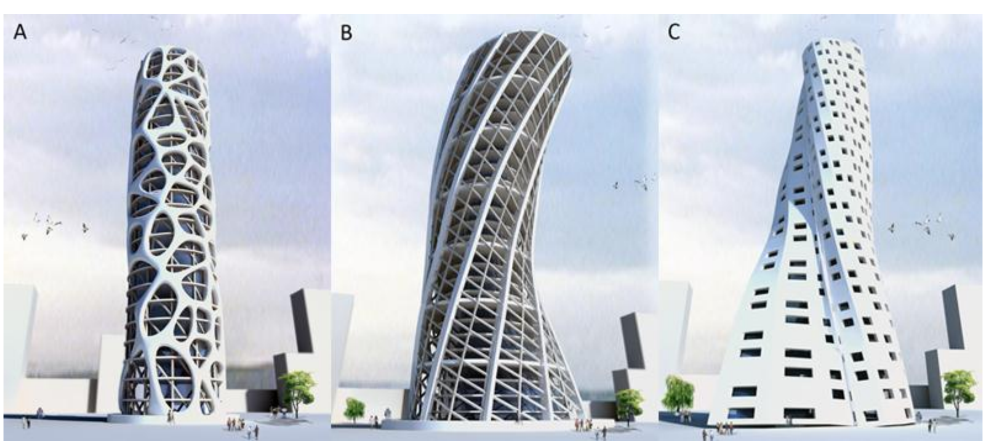


Figure (4-A, B and C): Show three different design solutions generated within the same model.

## DISSCUSSION

The results suggest that PDPs can overcome limitations of previous approaches. Designers can start with an infinite number of initial shapes to create a parametric skeleton and create a parameterized model on the skeleton to start with generating and exploring potential design solutions. After that, the initial shapes, parametric values and operations can be easily and quickly modified to achieve the goals of parametric modeling and overcome restrictions of geometrical and topological transformations (Figure 5).

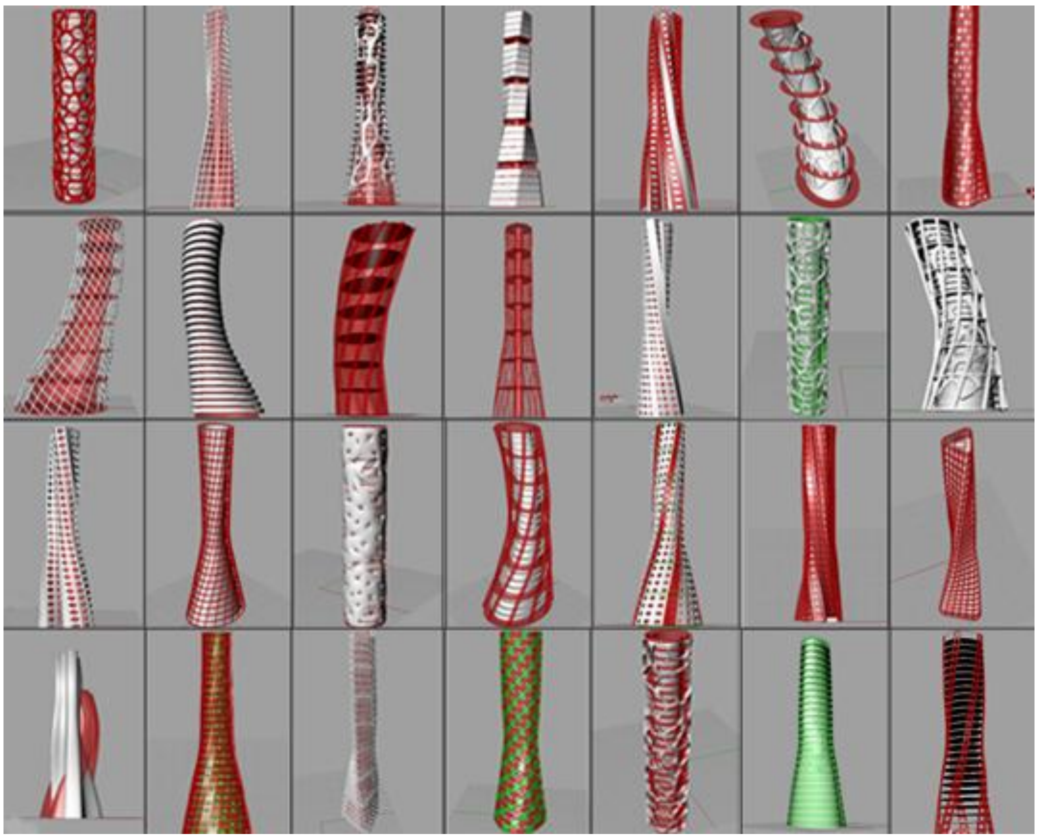

Figure (5): Different design instances generated using the same model.

Compared to other computational generative methodologies such as Transformations of Shape Grammars, the results suggest that PDPs were successful in providing an appropriate environment to generate unpredictable design solutions and designers have full control in a parametric way over all events. Compared to Design Procedures, PDPs provide designers another level of complexity which is easy to create and updating can be done automatically when changing any parametric feature (unlike DP which is very basic and does not allow designers to generate complex layers without writing a script). Also as the results indicate, PDPs generate all those design solutions using the same definition; using Design Procedure, designers must write codes to create any particular design. On the other hand, considering the difficulties and needs of the conceptual design phase, the results demonstrate that PDPs have the potential of addressing the needs of this phase of the design process (e.g. generating, exploring, and testing multiple design instances using the same parameterized model).

PDPs were also successful in promoting parametric design through achieving goals of parametric modeling and overcoming current restrictions of parametric design. For example, in allowing 2D and 3D transformation at any time (potentially overcoming topological and geometrical limitations of conventional parametric design), allowing any additional layers at any time during the design process without breaking the built model, creating multiple number of complex design solutions, and allowing designers to interact with the entire design process.

It should however be pointed out that the assessment of the potential benefits of prototype, although based on the predefined goals of parametric modeling and the needs of the conceptual design phase, was based on self-evaluation; a more robust evaluation (e.g. by professionals and potential users) is required to ascertain the real benefits of the system. Another limitation was that only one development environment (Grasshopper) was used; the implementation of PDPs in multiple environments will provide a better assessment of its capabilities in meeting the objectives for which they were developed.

## CONCLUSIONS AND RECOMMENDATIONS

The research was aimed at developing a new computational methodology for form generation focusing on the conceptual stage of design process. This was pursued through an identification of the goals and objectives of parametric modeling, the particular features of the conceptual design phase, and the limitations of existing generative systems. Results showed that, PDPs have the potential of achieving the goals which they were designed for. PDPs provide designers with an environment that design solutions can be easily and quickly generated in a relatively short time using the same parameterized model. Although the assessment of the approach was based on predefined goals of parametric modeling and needs of the conceptual design phase in the design process, the assessment was a kind of self-assessment which can be seen as a limitation of the study. Another limitation was related to the implementation environment as currently only Grasshopper software supports this approach. The need to develop and assess PDPs using other software environments and tools is a logical step for future research.

As a recommendation, PDPs as a collaborative computational methodology for form-generation can be applied to parametric systems and software which are used by architects. Given the potential of PDPs in the conceptual design phase, it is reasonable to assume that it will be appropriate to other phases of the design process. However, further research is required to explore this.

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# A FUZZY RISK MANAGEMENT FRAMEWORK FOR THE EGYPTIAN REAL ESTATE DEVELOPMENT PROJECTS

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**ABSTRACT**: This paper presents a fuzzy risk management framework which enables project management teams to detect and assess critical risk events in Egyptian Real Estate Development projects. The framework introduces three models that include: 1) Fuzzy Expert System (FES), 2) Fuzzy consensus-based model, and 3) Fuzzy Fault and Event Tree analysis model. The Fuzzy Expert System (FES) determines the importance weight factor for the experts, participating in the risk evaluation process, based on their qualifications. The Fuzzy consensus–based model is applied to aggregate experts' opinions in evaluating risks in a linguistic framework. The Fuzzy Fault, and Event tree model is used to support the decision-makers by identifying the critical root causes of the identified risks and hence develop a mitigation strategy to respond to the risks. Literature review and experts interviews identify risk events in order to determine risk categories relevant to real estate development projects. A Fuzzy Consensus Measurement approach integrates experts' opinion in a linguistic framework by computing a consensus weight factor for experts based on the proximity of their opinions on a linguistic scale. Experts' opinions are integrated using both the importance weight factor and the consensus weight factor of experts. Based on the aggregated opinions of experts, a Three-Dimensional Matrix Ranking Approach and preset experts’ rules are used to prioritize different risk factors according to their importance to real estate development projects. After detecting critical risk events, a fault and event trees analysis is conducted to calculate the probability of failure of critical risk events as well as the probability of failure of mitigation strategies. Moreover, the event tree analysis computes the cost of success of the mitigation strategy.

Author Keywords: Consensus Measurement Framework, Event trees, Fuzzy Expert System, Fault trees, and Risk Management Framework.

## 1. INTRODUCTION:

Risk management is an essential process in planning Real Estate development projects, which have great impact on the construction industry. The essentiality of risk management is greater in an industry that is characterized by being uncertain, such as the case of building construction. Moreover, the Real Estate industry plays a vital role in

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enhancing the economy of developing countries. For example, the Turkish real estate industry contributed to the Turkish Economy with US$10.4 billion of foreign investment, mostly by German, British and Greek citizens in 2008 (Chamber of Turkish Engineers and Architects 2008). Unfortunately, there is not enough research work that modeled such process in Real Estate projects in most of developing countries, especially in Egypt. As such there is a need to develop an integrated risk management framework to assess Real Estate risks in developing countries that specifically focuses on Egypt as a developing country that lacks research work in that field.

## 2. LITERATURE REVIEW:

Risk may have many interpretations and its definition can vary from one situation to another (Moskowitz and Bunn 1987). Chapmen (1998) defined risk as "the exposure to the possibility of economic and financial loss, or delay as a consequence of uncertainty associated with pursuing a particular course of action." Many authors have studied risk management from different perspectives. Zabaal (2007), who conducted construction risk research in Egypt, defined probability, which is one major component of a risk event, as the likelihood that a risk can occur. Also, he described the impact, which is another major component of a risk event, as the effect on the project objectives if the risk event occurs. Abdel gawad (2011) described level of detection, which is a recently introduced component of a risk event, as a means of which the system existed in a project can detect some of the potential risks before they occurs. Some researchers have tackled the issue of risk analysis to prioritize risk events from different perspectives. Also, Akinci and Fischer (1998) studied the risks that contribute to increasing the cost overburden on construction contractors. Another study was conducted by Wendling and Lorance (2000) who presented techniques for integrating the uncertainties associated with time and monetary resources when using the Monte Carlo simulation tool for risk analysis on capital projects. Zayed and Chang (2002) developed a prototype model for Build-Operate-Transfer risk assessment. Although research studies introduced risk management as important tool in dealing with uncertainties, most of them have not provided an integrated model or framework that incorporated consensus and quality of experts in the decision-making process of assessing risks, linguistically.

According to Herrera and Herrera–Viedma (2000), “those individuals (experts or decision-makers) are called on to express their opinions on a predetermined set of alternatives in order to select the best one(s)”. Elbarkouky and Fayek (2011) defined several elements that may cause expert' judgment to be different, such as academic experience, professional experience, position in their companies, the diversity of such experience, and willingness to provide information or data. Thus, the quality of experts is an essential factor in aggregating their opinions to make sure that their opinions are not flawed (Herrera et al. 1996). This is why there is a high demand to determine the importance weights of experts in deciding on their qualifications prior to assessing risks. Most often, real estate project teams have difficulty in evaluating risks encountered in their projects, while real estate construction firms depend on expert judgment in assessing these risk factors (Zabaal 2007). According to Elbarkouky and Fayek (2011*),* the two main issues that may affect the decision-making process are “extracting meaningful data from a group of experts, and combining the experts, subject opinions by resolving disagreements." This is the reason why there is a need to develop a framework to aggregate experts' opinions in prioritizing risks that can motivate expert judgment and deal with its relative vagueness and imprecision, linguistically. The framework should be also capable of assessing the quality of experts in the decision-making process and it has to enable experts to prioritize the risks, based on their probability of occurrence, impact, and level of detection/control. Finally, construction firms should be able to calculate the bidding price of a real estate project in different scenarios when the probability of occurrence of a risk event is uncertain. Therefore, the expected monetary value (EMV) of each risk event should be calculated in such framework that should be sufficient to accommodate the consequences of risk events.

## 3. RESEARCH OBJECTIVES:

The main objective of this paper is to propose an integrated risk management framework that identifies, qualifies, quantifies, and mitigates risk factors affecting Egyptian Real Estate Projects, linguistically. This framework combines Fuzzy Expert System (FES), Fuzzy Consensus Measurement Framework, and Event and Fault Tree analysis to assess risks in Building Construction and Real Estate Projects. The framework provides project teams with a useful tool that incorporates consensus of the project team members in performing risk criticality analysis of Real Estate project with the importance weight of each expert participated in the process of evaluating risks existed in Real Estate projects based on his or her qualifications.

## 2. METHODOLOGY AND MODEL DEVELOPMENT:

The framework consists of three models: Fuzzy Expert System Model (FES), Fuzzy Consensus Measurement Model, and Fault and Event Tree Model as future extension to the research (Figure 1).

### 2.1. Fuzzy Expert System Model:

The Fuzzy Expert System (FES) is composed of three stages: (1) data collection and variables' development; (2) fuzzy expert system (FES) model development; and (3) validation and sensitivity analysis. Figure 2 illustrates the basic components of the FES.

#### 2.1.1. Data Collection and Variables' Development:

The first step in developing the FES model involves defining its input and output variables, developing the scales that are used to define these variables, and defining the linguistic terms describing each of these variables, using experts' judgment. Step two involves constructing the membership functions of the input, and output variables, using the modified horizontal approach with interpolation technique. Step three involves deciding on the relative influence of the input variables on the output variable, which assists on developing the rule base of the FES. In this step, data are collected from experts, using a survey-based questionnaire and a 1-5 likert scale with 1 means "very low influence" and 5 means " very high influence."

#### 2.1.2. Fuzzy Expert System (FES) Model Development:

The second stage involves the FES model development, which includes the creation of the fuzzy expert system (FES) model that is implemented using FuzzyTECH®. FuzzyTECH® software motivates the creation of the knowledge base of the fuzzy-if-then rules, automatically, based on the influence of the input variables on the output variables.

**2.1.3. Validation and Sensitivity Analysis:**

The third stage involves the validation and sensitivity analysis to test the quality of the FES model. A case study is applied to determine the importance weight factor of a group of real estate experts in Egypt, based on their actual attributes. The output data of the model is to be validated through experts to provide an average assessment of the importance weights of the group of real estate experts. The average percentage error between the outputs of the model and the average rating of experts is calculated to validate the results of the model. Figure 3 illustrates the components of FES model.

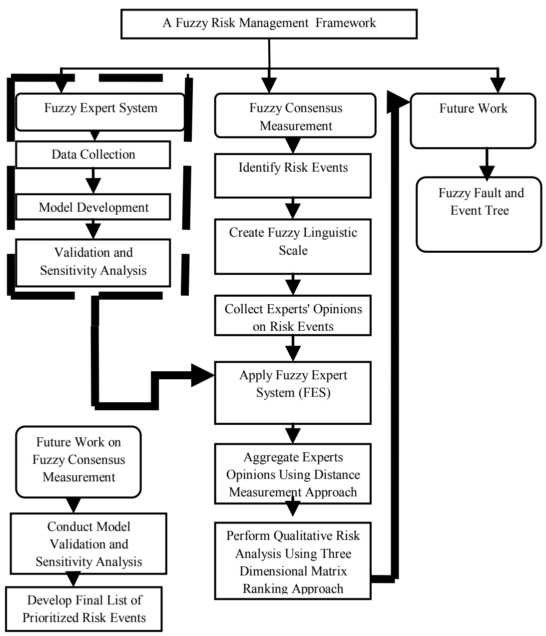


**Figure 1: Model Development.**

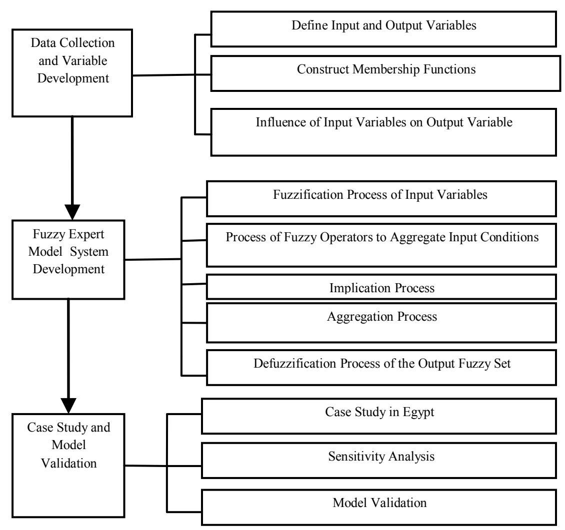


**Figure 2: Components of FES Model.**

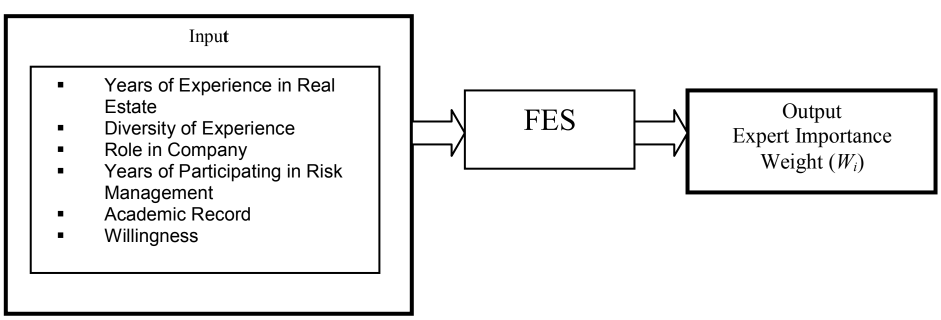


**Figure 3: Applied Components of FES Model.**

Table 1 shows a sample of the qualifications of experts and the results of the Base Case System that has been created using Fuzzy Expert System.

**Table 1: Sample Results of Base Case System and Experts' Qualifications**

| Exp. | Real Estate Experience | Academic Record | Willing | Diversity of Exp. | Role in Company | Years In Risk | Experts' Rating | Base Case | %Error |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 16-20 | Master | V .High | V .High | P.Manager | 16-20 | 0.967 | 1.00 | 3.448 |
| 2 | 1-5 | Bachelor | V .High | V .High | S.P.Engineer | 1-5 | 0.5 | 0.551 | 6.66 |
| 3 | 16-20 | Master | Average | Average | P.Manager | 16-20 | 0.683 | 0.65 | 4.561 |
| 4 | 6-10 | Bachelor | Average | V .High | P.Manager | 6-10 | 0.483 | 0.635 | 5.455 |

## 2.2. Fuzzy Consensus Measurement Model:

The Fuzzy Consensus Measurement Model is composed of seven steps.

### 2.2.1. Identify Critical Risk Events:

The first step is to identify critical risk events that may generally exist in real estate projects. Literature review and interviews, using the indirect method, with fifteen experts each of them has an experience of twenty years in Real Estate projects in developing countries identified 27 risk events and their relevant classifications (e.g., financial, real estate related, engineering, construction, etc.).

### 2.2.2. Create Fuzzy Linguistic Scale:

The second step is to create a fuzzy linguistic scale; through which real estate project teams can rank different risk factors affecting real estate development projects, according to the probability of occurrence, impact, and level of detection, linguistically. In this stage, interviews were held with the fifteen experts, and it was agreed by the experts to use a five-point Likert scale ranging from 1 to 5. 1 means " very low" , 2 means "low", 3 means "moderate" , 4 means "high", and 5 means "very high." Furthermore, interviews were held with experts to decide on different elements of the scales (Table 2) for probability of occurrence, impact, and level of detection, using two-steps Delphi technique. Figure 4 illustrates an example of the final shape of the membership function "Probability of Occurrence."

**Table 2: Group Scales Representation.**

| Input | Very Low | Low | Medium | High | Very High |
|---|---|---|---|---|---|
| Probability | 1-20% | 21-40% | 41-60% | 61-80% | 81-100% |
| Impact group 1 (Subjective items) | 1 | 2 | 3 | 4 | 5 |
| Impact group 2 (Percentage of increase) | 1-20% | 21-40% | 41-60% | 61-80% | 81-100% |
| Impact group 3 (Value of Cost Increase) | 1-200000EGP | 201000-400000EGP | 401000-600000EGP | 601000-800000EGP | 801000-1000000EGP |
| Impact group 4 (Value of Cost Increase) | 1-20000EGP | 21000-40000EGP | 41000-60000EGP | 61000-80000EGP | 81000-100000EGP |
| Level of Detection | 1-20% | 21-40% | 41-60% | 61-80% | 81-100% |

Experts recommended regrouping the risk events based on the different scales of the probability of occurrence, level of detection, and the risk impact groups' scale (Table 3).

**2.2.3. Collect Experts' Opinions on Risk Events:**

The third step is to collect project teams' rating of the risk factors affecting real estate projects using the linguistic terms that were created in step two.

**2.2.4. Apply Fuzzy Expert System (FES):**

The fourth step is to apply the Fuzzy Expert System (FES) to calculate an importance weight for each expert participating in the risk assessment process.

**Table 3: Different Risk Events Groups Recommended by Experts.**

| No. | Factors | No. | Factors |
|---|---|---|---|
| Group One | | 15 | Loss due to inflation |
| 1 | Delay of workshop Drawings | 16 | Increase in the registration costs |
| 2 | Incomplete design information | 17 | Increase in the regulation costs, such as increase in the cost of permits and licenses |
| 3 | Ambiguities, fault and inconsistent specifications | 18 | Currency Devaluation and variable rate of exchange |
| 4 | Design difficulty impacting construction work | 19 | Increase in real estate taxation |
| 5 | Delay of the owner progress payment to contractors | 20 | Increase in the borrowing interest rate |
| 6 | Increase in the government restriction to finance construction companies | 21 | Increase in income taxation |
| 7 | Decrease in the existence of financially credible contractors | 22 | Increase in customs |
| 8 | Poor labor productivity | 23 | Increase in the cost of disputes |
| 9 | Lack of project management | Group Three | |
| 10 | Incorrect data and information such as surveying mistakes | 24 | Increase in the price of raw materials |
| 11 | Damage or failure risks, such as cutting existing electrical / telephone cables | 25 | Increase in labor wages |
| 12 | Shortage of skilled contractors and subcontractors | 26 | Increase in the cost of equipment. |
| Group Two | | Group Four | |
| 13 | Increase in design fees | 27 | Increase in the cost of purchasing land |
| 14 | Increase in the underwriting costs | | |

**2.2.5. Aggregate Experts Opinions Using Fuzzy Distance Measurement Algorithms:**

The fifth step is to apply the distance measurement algorithm to aggregate experts' opinions by combining each expert's importance weight factor with his or her consensus weight factor, and determining the final linguistic value representing experts' opinions, which will be a non-uniform membership function on the scale. The distance measurement algorithm relies on the proximity of an expert's opinion relative to the other experts on the scale to ensure that experts' final decision is a result of their common agreement. Euclidean distance measurement function (Heilpern 1997) is then used for the purpose of relating the non-uniform membership function, representing the experts' group opinion, to the uniform membership functions on the scale and concluding meaningful linguistic terms that represent each risk event probability, impact, and level of detection. The linguistic term whose membership function has the minimum Euclidean distance to the aggregated non-uniform membership function representing experts' opinions on the scale describes the final extent of the risk factor affecting the real estate development project. For example, in order to determine the final linguistic term of a risk event, the Euclidean distance is applied between the quadruples ($r_1$, $r_2$, $r_3$, $r_4$) of the aggregated fuzzy number $R$ of experts and those of the five standard fuzzy ratings $Y_{(k)}$ on the scale where $P=2$ for the Euclidean distance measure, $n=4$ because each fuzzy number is represented by a quadruple, $r_i$ is the number element of each number $R$ on the scale (e.g., the support), and $Y_i$ is the corresponding number forming the quadruple of each of the standard fuzzy ratings $Y_{(k)}$ on the scale using Equation (1).

$$dg(R,Y) = \frac{\left(\sum_{i=1}^{n} |r_i - y_i|\right)^{1/p}}{n} \tag{1}$$

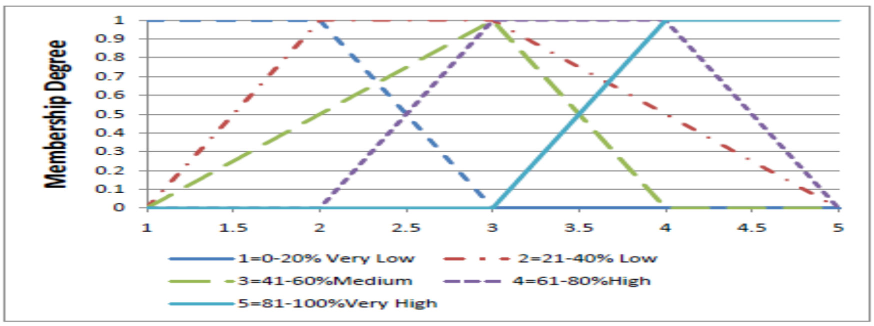


**Figure 4: Final Shape of Membership Function "Probability of Occurrence."**

Table 4 illustrates importance and consensus weight factors for thirty five experts who participated in the process of measuring consensus on the risk event "loss due to inflation."

**2.2.6. Qualitative Risk Analysis Using Three Dimensional Matrix Method:**

The sixth step is to apply the three dimensional ranking approach that utilizes specific linguistic ranking rules (Abdelgawad 2011) in order to produce a prioritized list of qualified risk events. Table 5 shows the fuzzy prioritization rules, whereas Figure 5 illustrates a visual prioritization of risk events, using three-dimensional ranking approach. Table 6 illustrates the final list of identified Risk Events affecting Real Estate Development Projects. The model validation and sensitivity analysis are currently under preparation.

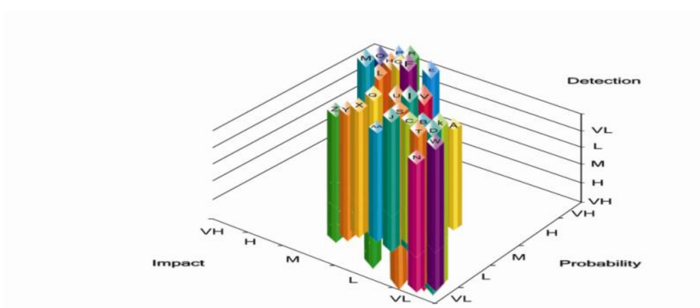


**Figure 5: Visual Prioritization of Risks**

**Table 4: Experts' Importance and Consensus Weights**

| Experts | Importance Weight | Consensus Weight | Experts | Importance Weight | Consensus Weight |
|---|---|---|---|---|---|
| **Expert1** | 0.0455 | 0.0375 | Expert19 | 0.0288 | 0.0288 |
| **Expert2** | 0.0250 | 0.0273 | Expert20 | 0.0320 | 0.0304 |
| **Expert3** | 0.0290 | 0.0295 | Expert21 | 0.0353 | 0.0320 |
| **Expert4** | 0.0353 | 0.0324 | Expert22 | 0.0319 | 0.0299 |
| **Expert5** | 0.0320 | 0.0308 | Expert23 | 0.0319 | 0.0303 |
| **Expert6** | 0.0182 | 0.0238 | Expert24 | 0.0227 | 0.0211 |
| **Expert7** | 0.0182 | 0.0238 | Expert25 | 0.0250 | 0.0269 |
| **Expert8** | 0.0182 | 0.0238 | Expert26 | 0.0319 | 0.0303 |
| **Expert9** | 0.0297 | 0.0296 | Expert27 | 0.0250 | 0.0269 |
| **Expert10** | 0.035 | 0.0324 | Expert28 | 0.0250 | 0.0269 |
| **Expert11** | 0.0182 | 0.0230 | Expert29 | 0.0250 | 0.0269 |
| **Expert12** | 0.0455 | 0.0371 | Expert30 | 0.0455 | 0.0371 |
| **Expert13** | 0.035 | 0.0320 | Expert31 | 0.0250 | 0.0264 |
| **Expert14** | 0.0216 | 0.0252 | Expert32 | 0.0250 | 0.0264 |
| **Expert15** | 0.0216 | 0.0252 | Expert33 | 0.0250 | 0.0264 |
| **Expert16** | 0.0267 | 0.0277 | Expert34 | 0.0250 | 0.0264 |
| **Expert17** | 0.0250 | 0.0269 | Expert35 | 0.0288 | 0.0284 |
| **Expert18** | 0.0288 | 0.0288 | | | |

**Table 5: Fuzzy Prioritization Rules**

| Rule Number | Probability of Occurrence | Impact | Level of Detection | Risk Criticality |
|---|---|---|---|---|
| **1** | M | L | H | L |
| **2** | L | L | H | VL |
| **3** | L | L | VH | VL |
| **4** | VL | VL | H | VL |
| **5** | H | M | VL | H |
| **6** | H | H | VL | VH |
| **7** | L | L | M | L |
| **8** | VL | L | H | VL |
| **9** | VL | VL | H | VL |
| **10** | H | H | L | H |
| **11** | VL | VL | VH | VL |
| **12** | VH | VH | VL | VH |
| **13** | L | M | M | M |
| **14** | M | M | VH | L |

## 2.3. Fuzzy Fault and Event Tree Model:

The third model in the Fuzzy Risk Management Framework is the Fuzzy Fault and Event Tree Model, which is composed of five stages: Data Collection, Qualitative Fault Tree, Quantitative Fault Tree, Analyze Mitigation Strategies, and Fuzzy Event Tree Analysis. The main objective of the Framework is to assess risks encountered in the Egyptian Real Estate Projects quantitatively. The framework is currently under preparation.

## Table 6: Final List of Identified Risk Events

| Risk Event | Point | Probability | Impact | Detection | Risk Criticality | Rank |
|---|---|---|---|---|---|---|
| **Loss due to inflation** | F | H | H | VL | VH | **1** |
| **Increase in the price of raw materials** | O | VH | VH | VL | VH | **1** |
| **Increase in the cost of equipment** | R | VH | VH | VL | VH | **1** |
| **Increase in labor wages** | P | VH | VH | VL | VH | **1** |
| **Currency Devaluation and variable rate of exchange.** | G | H | H | VL | VH | **1** |
| **Increase in the borrowing interest rate.** | H | H | H | VL | VH | **1** |
| **Decrease in the existence of Financially credible contractors.** | M | H | H | VL | VH | **1** |
| **Increase in design fees** | E | H | M | VL | H | **2** |
| **Increase in the government restriction to finance construction companies.** | L | H | H | L | H | **2** |
| **Poor labor productivity** | Q | L | M | M | M | **3** |
| **Lack of project management** | S | M | M | H | M | **3** |
| **Shortage of skilled contractors and subcontractors** | V | M | M | L | M | **3** |
| **Delay of work shop drawings** | A | M | L | H | L | **4** |
| **Increase in real estate taxation** | I | L | L | M | L | **4** |
| **Damage or failure risks** | U | L | L | M | L | **4** |
| **Increase in the cost of Disputes** | AA | M | M | VH | L | **4** |
| **Incomplete design information.** | B | L | L | H | VL | **5** |
| **Ambiguities, fault and inconsistent specifications.** | C | L | L | H | VL | **5** |
| **Design difficulty impacting construction work** | D | VL | VL | H | VL | **5** |
| **Delay of the Owner progress payment** | J | VL | L | H | VL | **5** |
| **Increase in the underwriting Costs** | K | VL | VL | H | VL | **5** |
| **Increase in the cost of purchasing land** | N | VL | VL | VH | VL | **5** |
| **Incorrect data and information such as surveying mistakes** | T | L | L | H | VL | **5** |
| **Increase in the registration costs** | W | VL | VL | H | VL | **5** |
| **Increase in the regulation costs** | X | L | L | H | VL | **5** |
| **Increase in income taxation** | Y | L | L | H | VL | **5** |
| **Increase in customs** | Z | L | L | H | VL | **5** |

## 3. CONCLUSION:

In this paper, a Fuzzy Risk Management Framework was proposed to identify, qualify, quantify, and develop response planning of risks encountered in real estate projects. The framework incorporated consensus, quality of experts, and Fault, and Event Trees (as a future extension of the research) in the process of evaluating risk factors affecting real estate projects. Risks were identified through literature review and experts' interviews and were prioritized using Three-Dimensional Matrix Ranking Approach. Consensus weight factor for each expert participated in the risk assessment process was determined, using the Fuzzy Consensus Measurement Framework. The findings of the Fuzzy Consensus Measurement Framework in terms of highly ranked risk events F, G, O, H, M, P, R, E, and L will be further quantified using the Fuzzy Fault, and Event Trees Model. The framework provides an improvement over the previous risk management models by incorporating the experts' qualifications, consensus weight factor of experts, and in the future Fuzzy Fault, and Event tree in evaluating risks in Real Estate projects in both qualitative and quantitative manners.

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# AN INTEGRATED MOBILE MATERIAL MANAGEMENT SYSTEM FOR CONSTRUCTION SITES

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***Abstract:***

Material management of construction projects is very important in view of cost control. Up to now, information systems that are operated on desktop computers are not so effective for the material management on construction sites. Though some mobile systems have been developed, they are not yet practical. This study aims to develop an integrated mobile material management system to improve this situation. QR code (Quick Response code) is used on mobile terminals for quick input of material data with a special tagging method reducing extra work, and both online and offline operations on mobile terminals on construction sites are supported. A framework is first established to integrate a mobile system with an existing information system. Then a mobile material management system is developed and integrated with an existing ERP (Enterprise Resources Planning) system through the Internet. The major part of the system is verified in an actual construction project.

Keyword: Construction site, Information system, Material management, Mobile terminal, Offline mechanism

## INTRODUCTION

Material cost accounts for up to 60 percent of total cost in some typical construction projects in China (Cai 1998), so that material management of construction projects is very important in view of cost control. Many construction firms have realized the importance to improve the material management by employing information technologies. Some firms have even implemented information systems such as ERP (Enterprise Resources Planning) systems, to achieve better management of all resources including materials (China Association of Construction Enterprise Management, 2009).

However, the existing information systems that mainly run on desktop computers cannot work efficiently for the material management on construction sites. It is because, in most cases, the materials on construction sites are stored far away from desktop computers in the office. As a result, warehouse keepers have to record management data in notebooks on site and then manually input the data into information systems after they return to office, which makes the material management on construction sites both inefficient and error-prone.

In recent years, development of mobile terminals, wireless network and Internet of Things provides new potentials for improving the material management on construction sites. RFID (Radio Frequency Identification Devices) technology has been a research hotspot in the material management for decades. Information systems based on RFID were developed to track steels (Chin et al. 2008), pipes (Ren et al. 2011) and structural components (Ju et al. 2012), and corresponding mobile systems based on a wireless network were also developed, which can significantly improve the material management on construction sites.

However, these systems are not yet practical since the unit price of RFID is too high considering the numerous components in a construction project, and there is no guarantee of satisfactory reading accuracy according to the results of field experiments (Song et al. 2006; Grau Torrent et al. 2009).

As a comparison, QR code (Quick Response code) shows its advantage in view of cost and accuracy (ISO/IEC 18004:2000, 2000) and is widely used for mobile applications such as ticket checking and product labeling because most mobile cameras can act as readers of QR code (Ohbuchi et al. 2004).

Furthermore, the wireless network is not always available for mobile terminals on construction sites due to environmental interference (Nuntasunti and Bernold 2006). In order to solve this problem, some major vendors of information systems have released corresponding tools, such as the Mobile Infrastructure 7.0 developed by SAP and the Application Development Framework developed by Oracle, to support both online and offline operations on mobile terminals. But up to now, systems developed by these tools are still too primitive to be applied in the material management on construction sites.

In order to improve the material management on construction sites, an integrated mobile material management system (MMMS) is developed. The QR code is used for quick input of material data with mobile terminals, and both online and offline operations on mobile terminals on construction sites are supported.

In this paper, at first, a special tagging method of QR code is adopted and the framework of MMMS is established. Then, the mechanism for offline operations is formulated. Finally, the implementation and application of MMMS are described.

## EXISTING PROCESSES AND USE OF QR CODE AND MOBILE TEMINALS

Through an in-depth investigation on three subway construction projects in China, the existing processes of the material management on construction sites and corresponding problems are summarized. Then it is decided to use QR code with a special tagging method and mobile terminals in this study to solve the problems.

### Existing processes

The material management on construction sites aims to control the movement of materials among warehouses, suppliers, builders and vendors. Through the investigation, the major existing processes of material management on construction sites are summarized as shown in Figure 1.

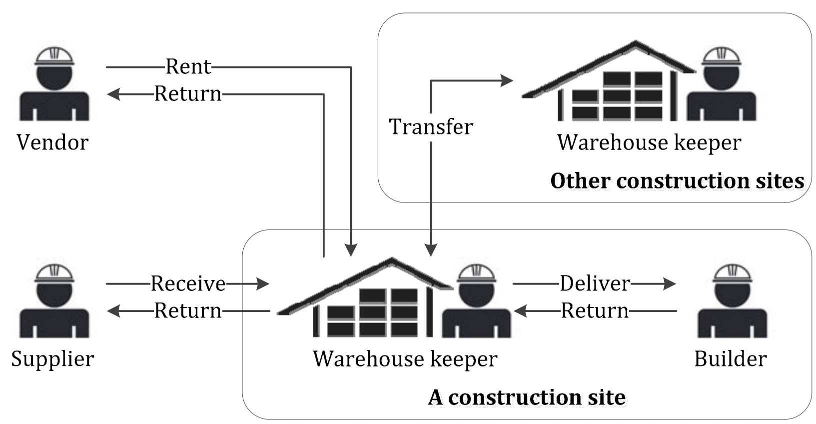


Figure 1 Major existing processes of material management on construction sites

Generally, all processes involve with three transactions, i.e. moving materials, checking with bills or inventory, and filling in forms. For example, when a warehouse keeper receives materials from a supplier, he checks the quality and quantity of each material according to the purchase order and fills the actual received quantities in relevant forms. If the check is passed, the materials are then stored in warehouses or open spaces; otherwise, they are returned to the supplier.

In many cases on construction site, materials are stored dispersedly, in temporary warehouses or in open spaces everywhere. So it is both labor-intensive and error-prone to record all management data on a notebook on site and then input them into an existing information system on computers after returning to office. In addition, the comparison between the relevant bills and the actual quantities also needs to be conducted in the office after the execution of on-site processes, causing extra cost of problem handling.

In order to solve the problems, QR code and mobile terminals are applied together, where the former is used to identify materials quickly and the latter is used to save the manual input of such information as the type of material or its code by scanning the QR code and to get necessary information on site from the information system.

**Tagging method of QR code**

As a kind of tag-based material tracking method, QR code has its limitations. Indeed, preparing and attaching tags involves extra work, and is error-prone, too. Besides, tags may come off or get damaged easily during the movement of materials (Ren, 2011).

| | |
|---|---|
| **Material ID:** | 3300000125 |
| **Description:** | Φ40mm Drill Stem of JackDrill |
| **Project ID:** | A01 |
| **Project Name:** | Subway No.14 in Beijing, 2010 |
| **Subinv. ID:** | A011 |
| **Subinv. Name:** | Subinventory of Auxiliary Materials in Area No.1 |
| **UOM:** | Meter |

Figure 2 A typical material tags of QR code

In order to overcome the limitations, the QR code tags (Figure 2) are attached on the Kanban boards rather than on the materials. These tags contain the information of the types of material instead of the materials themselves. Once a new open space or warehouse is assigned to store certain types of materials, a Kanban board is erected and corresponding tags are printed and attached. As materials move in and out, warehouse keepers use mobile terminals to scan the tags on the Kanban boards nearby for quick input. Since the types of material stored in one place are relatively unchanged, the extra work of attaching tags is ignorable and errors seldom happen. Implementation of printing and reading tags is presented in the following sections. By the way, RFID is not adopted considering its relatively high cost.

## FRAMEWORK OF MMMS

Figure 3 shows the framework of the integrated mobile material management system (MMMS). It consists of a server application and a mobile terminal application. The server application runs on a central server and invokes the APIs that encapsulate operations on the database of an existing information system while the mobile terminal application executes processes on construction sites and communicates with the server via wireless network. Compared to general frameworks of Client/Server architecture of web-based information system, three components are added into the mobile terminal application, i.e. a data switch module, client APIs and a client database. If network is unavailable, the data switch module sends requests to the client APIs instead of the server APIs, then responses are returned based on the client database. When it reconnects to the central server, the application will transmit all cached data and synchronize the client database with the server database.

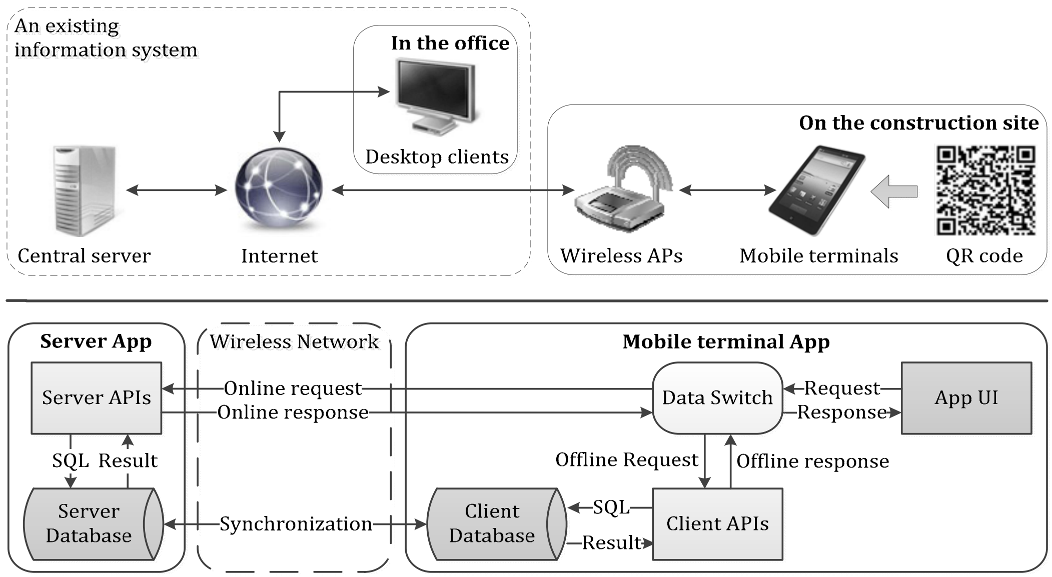


Figure 3 Framework of MMMS

Nine functions are included in the framework and they are classified into two groups, i.e. business functions and ancillary functions, as shown in Table 1. In addition to handling processes stated in Figure 1, the former ones are also used to manage inventory data and query relevant bills and forms, while the latter ones provide support for authorization and connection management. Besides, all business functions support offline operations, which are stated in the next section.

Table 1 Functions of MMMS

| Category | Function | Description |
|---|---|---|
| Business functions | Receiving management | Handle processes of the material management including input validation and business rules checking. |
| | Delivery management | |
| | Renting management | |
| | Transfer management | |
| | Inventory management | Check deviations between inventory and actual quantities. |
| | Material data query | Query material properties, relevant bills and forms. |
| Ancillary functions | User Account management | Manage user accounts and authorization. |
| | Connection management | Manage network settings and connections. |

## MECHANISM FOR OFFLINE MATERIAL MANAGEMENT

Since to obtain an online material management means to develop a web-based application, which is routine process nowadays, this paper omits it and concentrates on the mechanism for offline material management. According to literature (Fowler 1987), the lost update and inconsistent read problems are two basic offline concurrency problems in a network-based information system.

**Lost update problem of the offline material management and its solution**

The lost update problem of material management occurs when two processes update the same material data concurrently, and the prior update of the quantity of the same material may be lost as shown in Figure 4. It is avoided in some information system, for example, the Oracle ERP system, by inserting records of quantity changes in the database instead of updating the quantity directly. The actual quantity is calculated by summarizing all changes up for each query.

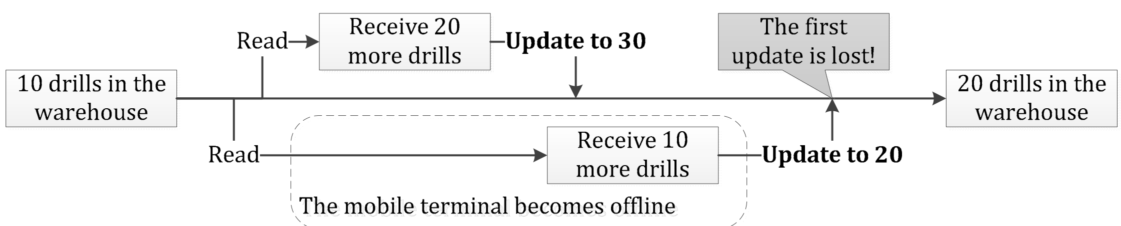


Figure 4 Lost update problem of the material management

**Inconsistent read problem of the offline material management**

When a process such as receiving materials is executed offline but not transmitted, the change of the inventory material quantities is invisible for other online and offline mobile terminals, then data read by other terminals is incorrect. When the wireless network is unavailable for hours, the incorrectness may not be noticed in time. This is the so called inconsistent read problem of the offline material management.

**Mechanism for inconsistent read problem based on pessimistic offline lock**

There is no perfect solution for inconsistent read problem to achieve both correctness and concurrency of data, and a tradeoff between them should be made based on the investigation of actual projects. On one hand, the correctness of data is important for processes validation and inventory management on site. If the correctness is not guaranteed, the warehouse keeper has to spend much time in counting the quantities of the materials in the warehouse since the data of the terminal may be incorrect. On the other hand, the concurrency of processes is relatively not so important and can be restricted. For each warehouse, one terminal is enough for material management. Thus, on the warehouse level, processes can be executed by only one terminal, which means the concurrency is restricted, while on the construction site level processes of different warehouses are executed concurrently by different terminals.

Therefore, a pessimistic offline lock is adopted to ensure correctness with some sacrifice of concurrency. The principle is as follows. When a process begins, relevant data is locked in all client databases and server database, so it prevents other processes from reading and writing the locked data until the current process ends. In this way processes on the locked data are forced to be executed sequentially and thus the correctness of the locked data is guaranteed.

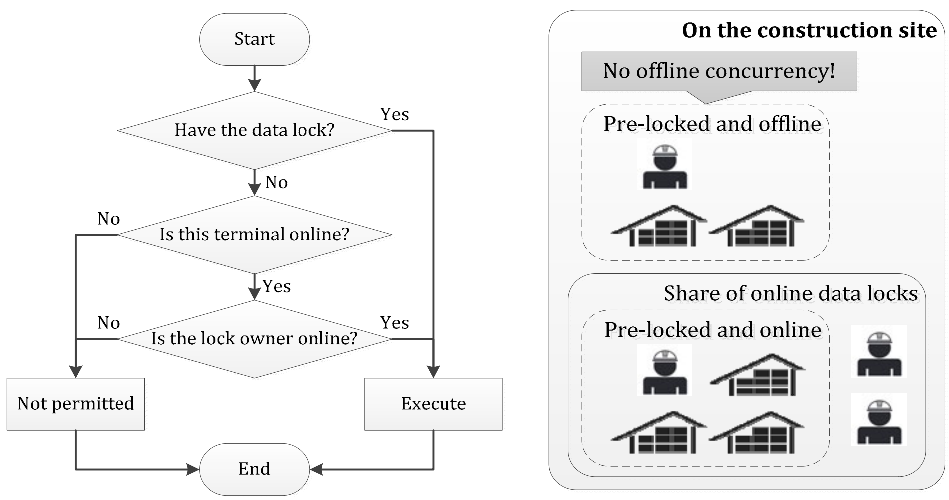


Figure 5 Mechanism based on the pessimistic offline lock

To apply the pessimistic offline lock, adjustments are made as shown in Figure 5. It is assumed that all warehouses are divided into groups and each group is charged by one warehouse keeper. In practice, this assumption can be satisfied easily. Since the time when the terminal is made offline is uncertain, the data needs to be pre-locked. When the warehouse keeper begins to work, he acquires the data lock of the warehouses he charges from the server application as soon as he logs in MMMS via the wireless network of the office. Then the mobile terminal application judges if certain process can be executed according to the algorithm shown in the left part in Figure 5:

(1) If the data lock of materials involved in this process is acquired by this mobile terminal application, the process is permitted regardless of the network condition.
(2) If the data lock has been acquired by other mobile terminal applications or the server application, and both this mobile terminal application and the lock owner are online, the process is also permitted since the locked data is synchronized.
(3) If the data lock has been acquired by others, but either this mobile terminal application or the lock owner is offline, the process is blocked.

Actually, the second situation above allows other applications to access the locked data. In other words, it shares the online data locks for convenience and flexibility of material management. Finally the data lock is returned to the server application via the wireless network when the warehouse keeper logs off MMMS after work.

## IMPLEMENTATION OF MMMS

The Android platform is chosen for mobile terminals because it is fully open for development and cost-efficient. The mobile terminal application is developed in Java and tested on the Galaxy Tab P1000. The client database is a SQLite database and an open-source project named ZXing is employed for QR code identification. An ERP system which has been customized for a subway construction company is integrated and the server database is an Oracle database. The following focuses on two technical issues of system integration and data synchronization while the implementation of the offline mechanism stated above is omitted.

**Integration with the existing information system**

Figure 6 shows the principle of integration in MMMS. First, APIs are developed based on the processes of the material management by PL/SQL, which encapsulate the operations of relevant data tables in the Oracle database. Then the mobile terminal application connects to the server application by sockets and the server application invokes the APIs by JDBC. A printer application has been developed for printing the QR code tags on site, and it connects to the server application by sockets, too.

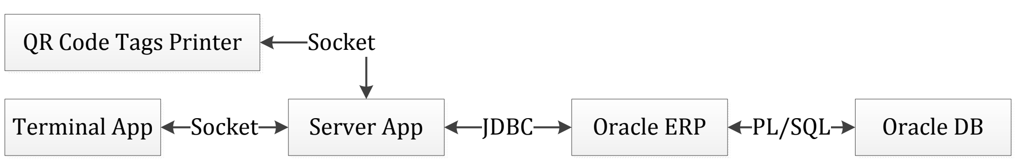


Figure 6 Principle of integration in MMMS

**Data synchronization**

All records in the Oracle database have a field named LAST_UPDATE_DATE, and the field is updated by the ERP system automatically. When the mobile terminal application connects to the server and sends a request for synchronization, the server application queries all records that are updated after the last synchronization time from the relevant data tables of the material management, packs them up and responds to the terminal. Then the terminal application unpacks the data and updates the client database.

# APPLICATION AND FEEDBACKS

The application of QR code tags, the integration of the system with an existing information system and mobile terminals that support both online and offline operations are three key parts of MMMS. The system is developed in two phases and most of the functions (Figure 7) except offline operations have been realized in the first phase and tested in an actual construction project. According to feedbacks from the practitioners in the test, the application of QR code with the special tagging method actually improves the efficiency of data input with little extra work, and data transmission between existing information system and mobile terminals has a good performance via wireless network. The second phase that implements offline functions has been carried out and the latest system will be delivered to production test soon.


Figure 7 UI of the mobile terminal application of MMMS

# CONCLUSIONS

This research developed an integrated mobile material management system for improving material management on construction sites. An in-depth investigation on the processes of the material management on construction sites was carried out and the existing processes and corresponding problems were identified. A framework was established for the integrated mobile material management system, in which QR code and mobile terminals were used with a special tagging method to reduce extra work and the mechanism for the offline material management was designed. Most of the functions except offline operations were implemented and verified in a project. It shows the potential and usability of QR code in material tracking, and the approach for integrating mobile terminals with existing information systems may be a sample for other studies. The offline mechanism should be an innovation in implementing mobile terminals in construction industry but the tradeoff between correctness and concurrency is a limitation.

To implement MMMS in the real project, further research and development are needed, i.e. to finish the development of offline operations and test them in actual projects, and to analyze and quantify the advantages and disadvantages of MMMS.

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# SPATIAL MAPPING APPROACH TO COMPONENT TRACKING USING RTLS SYSTEM

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## ABSTRACT

There have been several approaches to tracking the position and status of components using RFID tags. Some of these approaches still involve manually embedding status information in the tags. As such, access to real-time information depends on workers motivation and this can affect decision making. Other approaches also involve the use multiple radio frequency identification (RFID) readers on the job site which could be costly. However, opportunities exist for tracking the position and status of components by spatially mapping the job site using real-time location sensing (RTLS) system. The spatially mapped locations could be linked to building information models for automatic real-time position and status update. This paper describes experiments geared towards real-time tracking of tagged components by spatially mapping the job site. RTLS tags were used for tracking the position and status of components from on-site entry to installation. The experiments showed that these RTLS tags were more effective than standard RFID tags for position sensing and for automatically updating the virtual model. This approach also showed significant opportunities for enhancing real-time monitoring with minimal manual effort, which will aid proactive decision making and control. The key benefits of this approach are also highlighted in the paper.

**Keywords:** RFID-RTLS System, Spatial Mapping, Virtual Model and Physical Components

## INTRODUCTION

Studies indicate that construction personnel spend significant amount of time manually tracking and recording of progress data (Cheok et al. 2000; Navon and Sacks, 2007). Data collected using manual methods are usually not reliable or complete due to the reluctance of the workers to record these data (Ergen et al. 2007). An aspect of this data gathering process involves tracking the status of materials (such as when there arrive on site, where they are located, where and when they are installed). Being able to effective track the status of components on the job site will enable enhanced progress tracking and active decision making. Although, a number of researchers have proposed approaches to tracking components ranging from the isolated use of RFID tags (Song et al. 2006; Goodrum et al. 2006; Ergen et al. 2007; Razavi and Haas, 2011) to the use of integrated approaches such as the integration of RFID tags and virtual models (Chin and Yoon, 2008; Wenfa, 2008; Motamedi and Hammad, 2009). These approaches still involve manually embedding status information into the tags; thus the access to real-time information will depend on workers motivation. Opportunities exist for improving on current practices or existing component tracking approaches through the development of an automated status tracking system with minimal human input. Such system will enable real-time component level progress tracking.

Radio frequency identification Real-time location sensing (RFID-RTLS) system is capable of providing locations of tagged components within spatially mapped locations (installation points) or zones (staging areas, storage areas and unsafe zones) on the job site. Tightly integrating the tagged components with the virtual models (in an adaptive way) provides opportunity for real-time component status tracking without manually embedding information in the tags. Although, Akanmu et al. (2011) demonstrated the potential of RFID-RTLS system for tracking the 'installed' locations of tagged components, the goal of this research is to extend their work by investigating the potential of RTLS system for adaptive component status tracking from arrival on site until installation.

Thus, this paper focuses on describing experiments to tracking the status of construction components by spatially mapping the job site and automatically updating the virtual model using the RFID-RTLS system. This paper presents an overview of the RFID-RTLS system. A prototype system is developed and tested indoors and outdoors to demonstrate the functionality of the system. Experimental results are presented in the concluding section of the paper to illustrate the performance of the developed system.

## PERTINENT LITERATURE

Over the years, automated tracking of materials on the construction site has become technically more feasible with recent advances in automated acquisition technologies. Among these technologies, RFID technology has drawn a lot of attention from researchers investigating effective ways to automatically track the location of construction materials or components on site. These approaches range from component or tool tracking (Goodrum et al. 2006) to investigating the performance of RFID for identification during delivery and receipt of components on the job site (Yagi et al. 2005; Song et al. 2006). These approaches either involved manually scanning the tagged components with handheld readers or scanning the components at a fixed portal as a trailer with components arrives on the job site. These approaches were further improved upon by Ergen et al. (2007) who developed a prototype for tracking precast components in the predefined geo-referenced or mapped locations of storage yard using RFID and GPS technology. This approach demonstrated the potential of these technologies for tracking precast components without manually embedding status information in the tags. However, the use of GPS makes their approach limited to outdoor environments. For component installation status tracking, as the tracked components transition from outdoor to indoor locations (as the building becomes partially completed), the use of GPS becomes ineffective for installation status tracking.

Owing to the need for visualizing the status of tracked components for effective progress monitoring, other researchers have also proposed approaches to integrating the physical tagged components with the virtual models using RFID technology: Chin et al. (2005) who proposed the integration of 4D CAD and RFID tags for progress monitoring in supply chain management. RFID tags were placed on structural elements such as structural steel and curtain walls, to sense their status from the ordering stage through the delivery, receipt, and finally to the erection stage. The sensed status was captured in a 3D model to indicate progress status. Wenfa (2008) developed an integrated model of RFID and 4D CAD for tracking the status of construction components. Construction components (such as pipes, equipment, steel columns and beams) are tagged with RFID passive tags and an RFID reader is used to track their status from the manufacturing or fabrication plant to the construction site where they are installed. Motamedi and Hammad (2009) investigated the use of active RFID tags and BIM for lifecycle management of facility components. The authors proposed permanently attaching RFID tags to facility components where the memory of the tags is populated with BIM information. There has also being attempts by the industry to integrating field BIM and precast concrete installation using RFID tags (Sawyer 2008). The status of tagged precast concrete pieces was tracked from the fabrication yard to installation. The pieces are identified through the use of a RFID reader communicating with a Tablet PC that has Vela Systems Materials Tracking software installed. The limitation of these integration approaches is that access to status or progress information is dependent on when the construction personnel embeds information into the tags. Thus, opportunities exist for an automated approach to capturing status information of tagged components without manually embedding status information in the tags.

Unlike the RFID system, the RFID-RTLS system has shown great potential for both outdoor and indoor component tracking applications by providing location information of tagged components. An important distinguishing feature of this technology is its ability to zone or map defined areas of interest. This feature makes the RFID-RTLS system suitable for tracking the status of tagged components within mapped zones such as staging areas, storage areas and 'as-built' installation points in buildings. Being able to capture this status information provides opportunity for automatically updating the virtual model for progress monitoring. A recent study by Akanmu et al. (2012) involved the use of RFID-RTLS system for bi-directional coordination between virtual models and the physical components. In this study, a laboratory scale prototype was developed to demonstrate the potential of the RFID-RTLS for tracking 'installed' location of tagged components. This paper extends their work by conducting experiments to determine the accuracy of the RFID-RTLS system for automatically tracking the status of tagged components from arrival on site to installation by spatially mapping the job site. The captured status information will be updated in the virtual model for progress monitoring.

## OVERVIEW OF RFID-RTLS SYSTEM

The RFID-RTLS system obtained from Convergence System Limited consists of a master reader (CS5114), four slave readers (CS5112), one slave reader (CS5111), one Omni-directional slave reader (CS5116), ten RTLS tags (CS3151TC) and location engine software. The RFID-RTLS system is based on the theory of time-of-arrival (TOA) of radio frequency signal, where distance between the tags and reader (active readers at known reference locations) are determined by the round-trip time of the signal travelling between the two entities. By obtaining multiple range values (at least three), the exact x and y locations of the tags are figured out based on triangulations. The overview of the RFID-RTLS system is shown in figure 1.

- **RTLS Tags:** These are battery powered active tags usually attached to assets and personnel being tracked. The tags relay information every preset time interval (also known as cycle time) to the master and slave reader.

- **Slave Reader:** The slave readers determine the range of the tags and relay that data to the master reader.
- **Master Reader:** In addition to determining the range of the tags, the master reader also captures the data from each slave reader and relays it to the location engine software (installed in the associated computer system).

- **Location Engine Software:** The location engine software processes the ranging data from the readers and provides coordinates of the active tags.

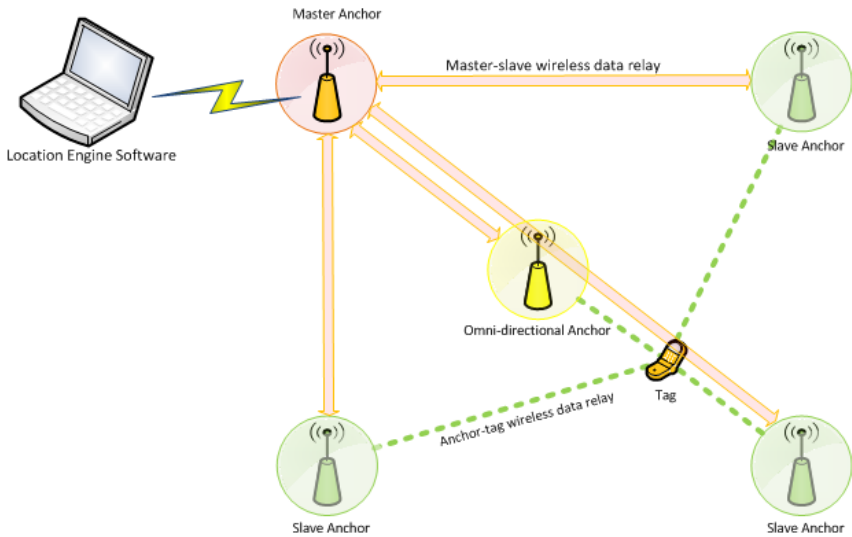


Figure 1: Component overview of the RFID-RTLS system

## PROTOTYPE SYSTEM

The prototype system was developed by integrating a physical laboratory scale prototype (Figure 2) and its corresponding virtual model using the RFID-RTLS system. The overall setup of the prototype system is shown in Figure 3. The key steps involved in the prototype system development include the following:

### Development of the Virtual model

A virtual model of a small scale building was developed using Autodesk Navisworks. The model serves the purpose of enabling visualization of status of tracked building components and information captured from the project site. The model also enables embedding of model updates or critical information that needs to be communicated to the construction site in real-time. Navisworks was utilized because it offers an open .Net application programming interface (API), which enables users to write custom plug-ins to drive Autodesk Navisworks from outside the graphical user interface (GUI) and automate tasks like changing material properties.

## Development of the Physical Laboratory Scale Model

A laboratory scale physical prototype of the Navisworks model was constructed. The physical prototype was 1m x 0.75m x 1m in dimensions and consisted of six detachable components (Figure 2). The physical prototype was designed as detachable components to enable easy removal when tracking placement during the experiment. The components of the laboratory scale physical building prototype were tagged with RTLS tags as shown in Figure 2.

## Development of Prototype Application

A prototype application was developed to integrate the virtual model and the physical laboratory scale prototype using Visual Studio .Net. The prototype application demonstrates the potential of the developed system for:

- Communicating with the RFID-RTLS system reader to acquire location coordinates and tag ID data;
- Collecting the location data of each tagged component;
- Assigning the status of 'On-site', 'Stored' or 'Installed' to each component based on the comparison of the location and planned location;
- Storing the captured location data and status for each tagged component in a MySQL database and;
- Monitoring changes in the database and reporting the updates in the virtual model based on the status updates of tags.

Figure 2: Laboratory Scale Physical Prototype

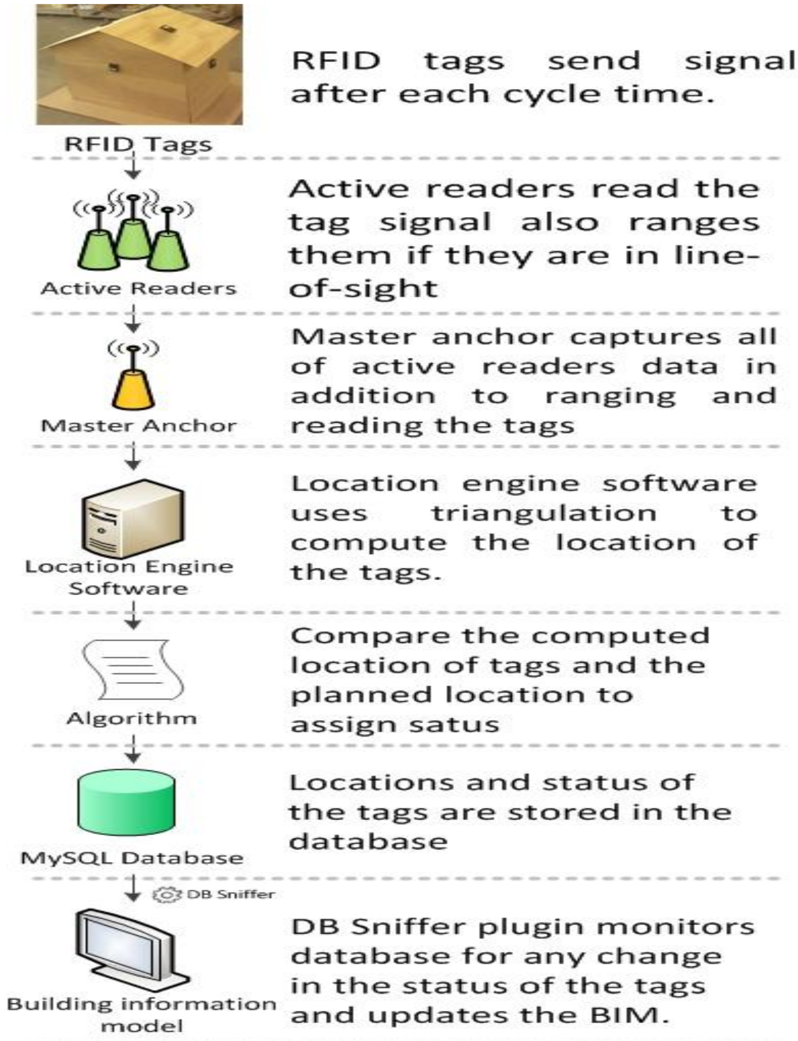


Figure 3: Prototype system overview

## EXPERIMENTAL PROGRAM

To determine the accuracy of the RFID-RTLS system for tracking components in mapped locations (such as entrance to site, staging areas and 'installed' locations), two experiments were conducted indoors (laboratory) and outdoors (field) environments. The details of the experiments are described below:

### Indoor Experiment

The indoor experiment was carried out in the Automated Systems Laboratory in the Department of Civil and Construction Engineering, College of Engineering and Applied Sciences, Western Michigan University, Kalamazoo. The aim of this indoor experiment was to test the functionality of the developed prototype system, prior to testing in the outdoor environment. The laboratory was mapped out as a "construction site". The master and slave readers were deployed at varying interval from 4m-13m on the perimeter of the laboratory. However, the omni-directional reader was placed in the center of the laboratory to ensure $180^0$ coverage of the laboratory. An assumed area of 2m x 2m was also mapped out for component storage. The physical laboratory scale prototype was placed at a known location within the laboratory (this indicates the as-built location of the physical prototype). The plans of the laboratory test area indicating the locations of the readers, staging area and the physical laboratory scale prototype are shown in Figure 4.

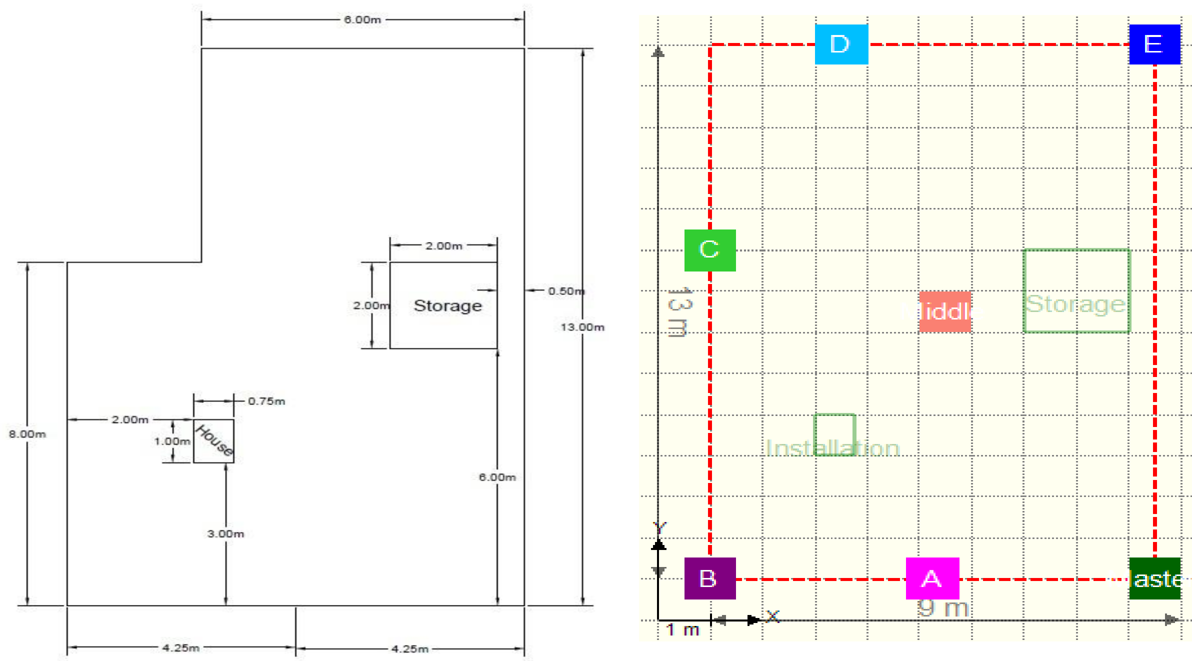


Figure 4: Physical Plan of indoor testing area (left), RFID-RTLS map showing mapped locations and locations of the readers (right).

## Outdoor Experiment

The outdoor experiment was carried out in the employees parking next to the College of Engineering and Applied Sciences, Western Michigan University, Kalamazoo. An area of 6m x 12m was mapped out as the "construction site". An assumed entrance was also mapped out. The readers were deployed at an interval of 6m on the perimeter of the mapped area with the exception of omni-directional reader which was placed in the middle of the mapped area. A storage area of 2m x 2m was also mapped out within the already mapped 'construction site'. The plan of the test area showing the location of the readers is shown in Figure 5.

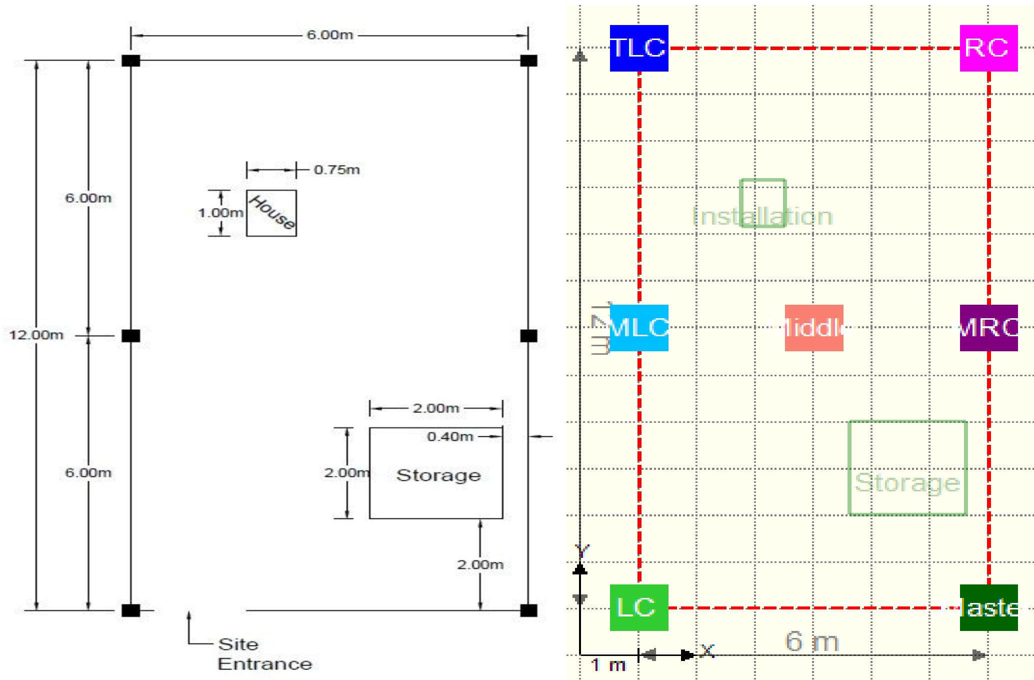


Figure 5: Plan of outdoor testing area (left), RFID-RTLS map showing the mapped areas and the location of readers (right)

**Methodology**

For both the indoor and outdoor experiments, positions of the readers were captured manually and defined in the prototype application along with the storage and the installation locations for the tags. The laboratory scale prototype components which include walls and roof components were tagged. The logistical sequence of the components was simulated similar to the actual construction site. The sequence commenced by bringing the components on-site, then storing the components in the storage area and finally installing the components in the as planned installation location. During the experiment, the following parameters were noted:

- The range of the tagged components from each reader as determined by the system. The RFID-RTLS system uses this data to compute the estimated location of the tagged components;
- The actual location of each tagged component. Measuring the actual location of the tagged components is important for determining the accuracy and reliability of the RFID-RTLS system for components status tracking. This can be compared with the estimated location to identify the deviation or localization error;
- The time of recognition of the tags by the RFID-RTLS system as the tagged components arrives into the observation area. This is important as it determines when the virtual model will be updated of the status of the tagged component and;
- The actual time of introduction of the tags into the observation area.

The above parameters were captured at every stage of the sequence i.e. during component arrival on site, in the storage area and in the 'installed' location or position.

# RESULTS

## Developed Prototype System

The developed prototype system was clearly able to track and capture the status of tagged components from on-site delivery to installation. Whenever the location of the tagged components changed, the colors of the corresponding virtual components were automatically updated. For example, the color of the virtual component changed to red when the corresponding physical component was on-site, changed to white when the corresponding physical component was on storage area, and finally changed to green when the corresponding physical component was installed. Figure 6 shows the update in virtual component color as a result of the components' status change.

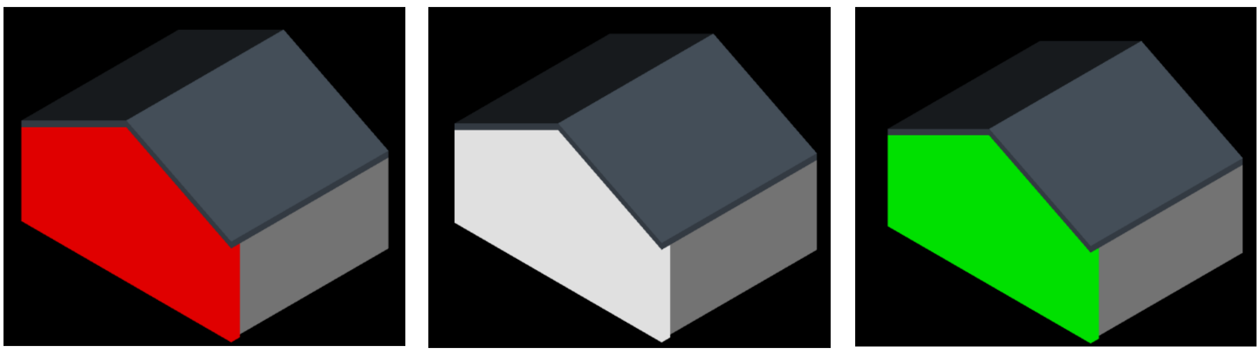

Figure 6: BIM alerting that the wall component is on-site (left), stored (center), installed (right)

## Test Results

The aim of the test was to determine the accuracy of the RFID-RTLS system for tracking components within spatially mapped locations and updating the virtual model with the status information. For both the indoor and outdoor tests, the actual and estimated locations of the tagged components were captured. The accuracy of the RFID-RTLS system was determined by computing the localization error for each tag. The localization error is the distance between the estimated location and the actual location. This was calculated in meters using both the estimated x and y coordinates of the tagged component (i.e., the tag) obtained from the RTLS, and the actual location of the tags (i.e., actual x and y coordinates).

$$\text{Localization error} = \sqrt{(\text{Actual x coordinate} - \text{Estimated x coordinate})^2 + (\text{Actual y coordinate} - \text{Estimated y coordinate})^2}$$

The estimated location of the tagged components within the mapped out locations was captured for about 45-60 seconds to determine the stability of the RTLS system data. It is important to have a stable location data so that the status update to the virtual model is stable. Figure 7, 8 and 9 shows the localization error for one of the tagged components. Figure 7 shows the localization error for one of the tagged components (for the indoor and outdoor experiment) computed for 45 seconds when the components where brought within the on-site mapped area. The localization error was higher indoors than outdoors due to multipath effects experienced with the laboratory. The outdoor localization error was less than 0.5m and this indicates that the tagged components are within the 'on-site' mapped area.

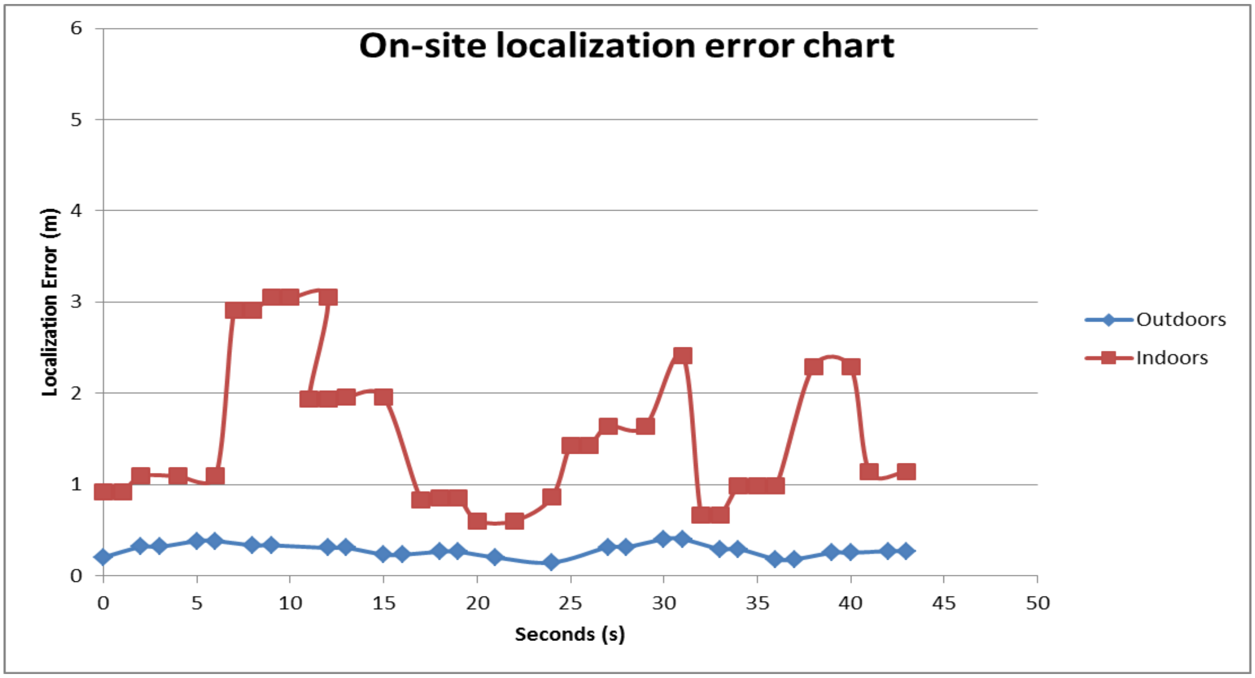


Figure 7: 'On site' localization error chart for indoor and outdoor experiment

Also, from Figure 8, the localization error observed for 60 seconds (while the tagged component was within the storage area) is less than 0.5m. However, the goal of tracking the status of the components is to have the model updated when the components are within the mapped location. Thus, the localization error is acceptable as this indicates that the component is within the mapped out location coordinates. This provided a stable status update to the model.

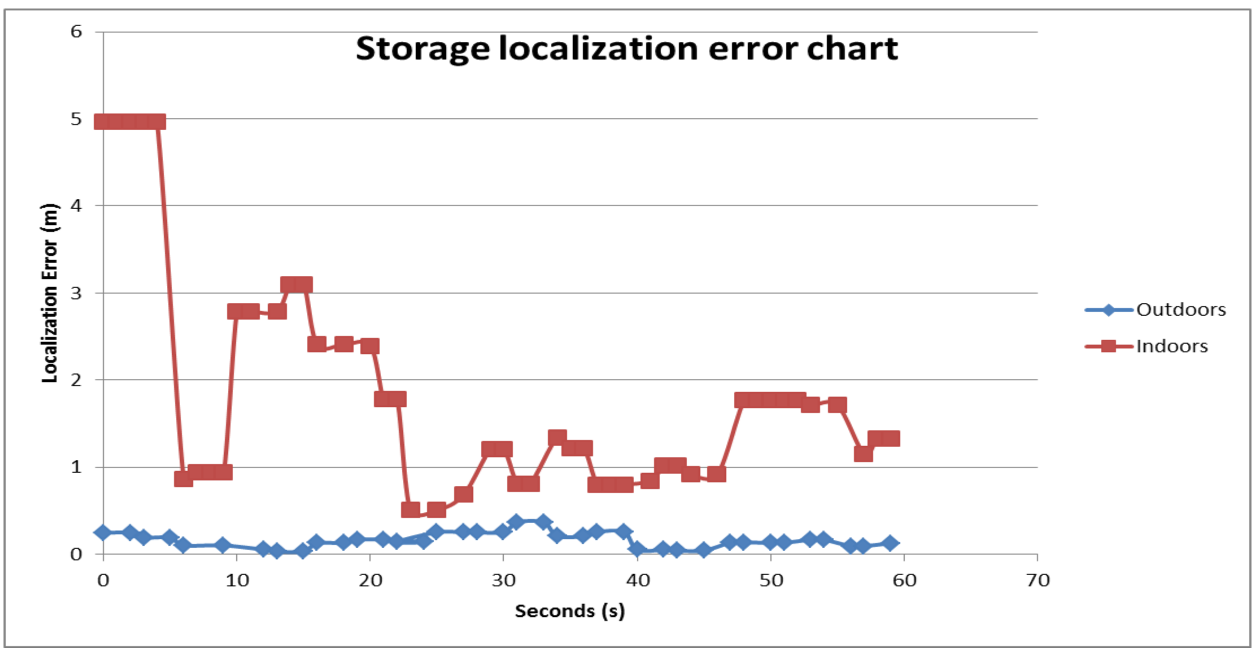


Figure 8: 'Storage area' localization error chart for indoor and outdoor experiment

For the 'installed' location tracking (Figure 9), the localization error was higher indoors than in the outdoor environment. However, in the outdoor environment, the localization error was less than one. This resulted in false and delay in virtual model updates. Even when the component was installed, the virtual model sometimes indicated that the component was uninstalled. The level of accuracy needed for tracking 'installed' status of the tagged components is high. Thus, it was necessary to have no localization error for 'installed' location tracking. Accuracy in 'installed' location tracking provides opportunities for real-time construction progress tracking by integrating the developed prototype system with schedule and cost forecasting applications such as earned value analysis. As extreme accuracy of the RTLS system is required for real-time update of status information in the model, there is need to further investigate how the accuracy of the RTLS system can be enhanced to reduce the localization error for capturing status at defined locations or points (such as the 'installed' locations).

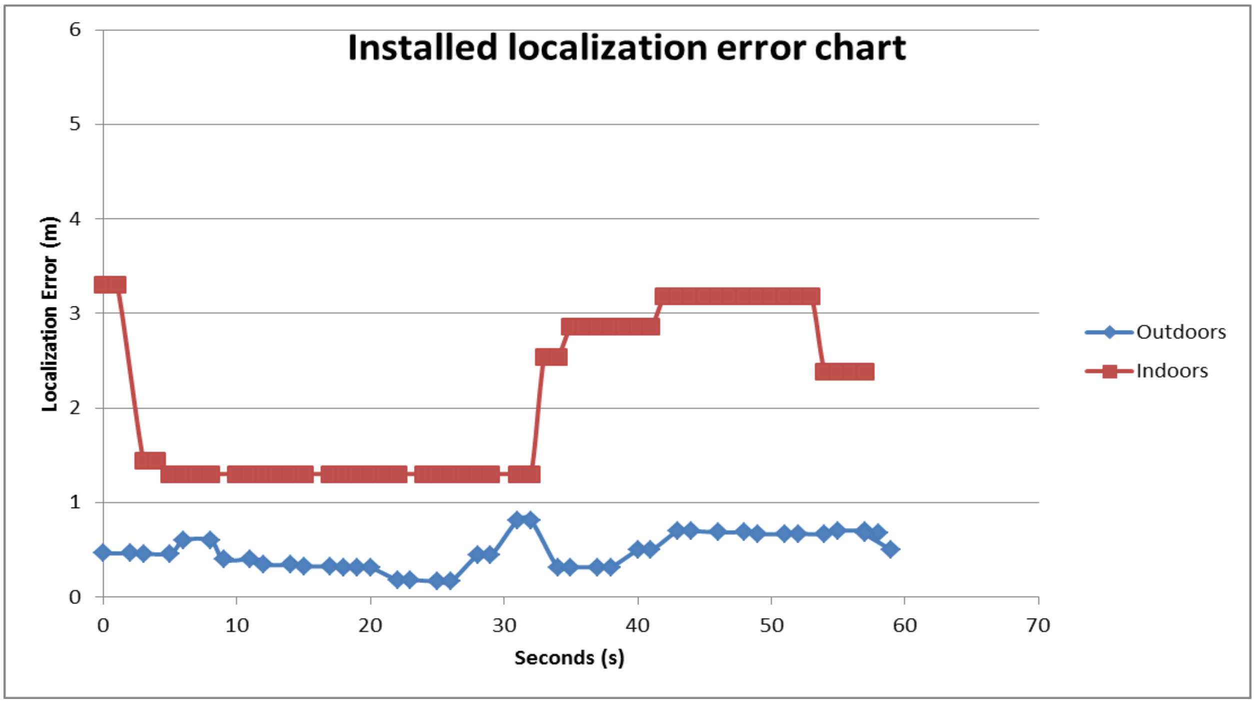


Figure 9: 'Installed location' localization error chart for indoor and outdoor experiment

## CONCLUSION

This study has demonstrated the potential of RFID-RTLS system for spatially mapping the job site for the purpose of tracking the status of tagged components from arrival on-site to installation. A prototype system has been developed. The developed system was tested in the laboratory to examine the functionality of the developed system prior to testing in an outdoor environment. The spatial mapping approach presented in this paper demonstrates how the RFID-RTLS system can be used for automatically capturing the status of tagged components without manually embedding status information in the tags. The key conclusions that can be drawn from this work are:

- The RFID-RTLS system is more accurate outdoors than in the indoor environment due to higher multipath effects experienced within indoor environments.
- The RFID-RTLS system proved more effective providing the status of components within large mapped out areas such as the staging area and construction site than for specific exact locations (installation points).
- The proposed approach is also applicable to automated site layout generation. The RFID-RTLS system can be used to spatially map the job site to track real-time status of personnel, materials and equipment. The captured status information, project and material schedule from BIM and Geographic information system (GIS) map of the job site can be integrated with optimization algorithms (such as genetic algorithms) for the purpose of automatically generating site layouts (in real-time). Other applications include spatially mapping unsafe areas or zones on the jobsite; tagging construction personnel hard hats to monitoring and automatically alert workers as they approach unsafe areas or zones on the job site. This will involve investigating localization algorithms to stabilize indoor accuracy so that workers status can be effectively tracked as they transition from outdoor to indoor environments and vice versa.

Further work includes experimenting with the physical laboratory scale prototype to investigate how the accuracy of the RTLS system can be improved as components transition from outdoor to indoor environments (in the case of a partially completed site). Being able to improve the indoor and outdoor accuracy of the prototype system offers opportunity for linking the system with progress tracking applications such as earned value analysis. This will aid generation of real-time schedule and cost of on-going construction projects for active decision making.

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# IPD IN PRACTICE: INNOVATION IN HEALTHCARE DESIGN AND CONSTRUCTION

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## ABSTRACT

In this paper we present a healthcare case study that leveraged Integrated Project Delivery (IPD), Building Information Modeling (BIM) and lean construction (Lean). With this project, we aim to investigate organizational alignment and focus on how team building facilitated innovation in the design and construction processes and had significant positive impact on the operational efficiencies of the building. Through structured interviews, we found that a unique proposal process, which was focused on "building team chemistry and understanding", lead to the team's development of a culture of open communication and teamwork that set the ground work for designers and builders to work closely together, blending teams and blurring boundaries throughout the execution of design and construction. In this paper, we explore how "The IPD allowed the overlaps to occur in a productive way". In doing so, we build on previous finding that the antecedents of effective integration were the development of the team's orientation and culture as well as the processes of working together. The tools, IPD, lean and BIM, supported the integrated teamwork, but did not create the integrated team; however, the contract, lean and BIM tools did reinforce the project team's integration and facilitated better results in terms of design and construction products. In this paper, we focus on how the drive for efficiencies in construction and operations influenced design processes and outcomes, and how team alignment overcame technological and logistical challenges throughout their project process.

## KEYWORDS

Building Information Modeling, Healthcare Design and Construction, Integrated Project Delivery, Lean Construction, Teamwork

## INTRODUCTION

The goal of this paper is to explore new and emerging practices that seek to integrate design and construction teams, foster collaboration and counter the negative effects of fragmentation, e.g. duplication of effort, miscommunication, errors and rework.

This study aims to understand how and in what ways design and construction teams are adopting and adapting Integrated Project Delivery (IPD), Lean Construction and Building Information Modeling (BIM) processes, tools and strategies in the effort for better coordination and collaboration across traditional organizational boundaries. To answer questions of how and why, we utilize a case study methodology (Taylor, et. al. 2011) to build theory that is grounded in practice. We selected a case which was pushing the IPD envelop with a visionary owner, designer and contractor. In this case, the project participants had not previously worked together, which provided an opportunity to study how a team adapts to new practices.

The Virginia Mason Health System was founded in 1920 with a mission "to provide a single place where patients could receive comprehensive medical care." (Virginia Mason 2012, n.p.). With a mature lean healthcare culture, known today as Virginia Mason Team Medicine, the hospital management is committed to bringing lean to their capital projects as well. The Virginia Mason Hospital has completed a new 16-story core and shell tower at the heart of an urban campus on First Hill in Seattle, Washington. As funding becomes available, they hire teams of designers and contractors to build out the tenant spaces. It is the story and experience of one such team that is present in this paper. This is a case of successful team integration. As the contractor reflected "*It is hard to have three friends because there is always one guy on the outside and that's why construction is really messed up ... the owner pits the design and construction off each other or the owner and contractor get on against design and all the rest of it. That never happened here."* Furthermore, the generalizable findings from this case point to a trend that the authors have seen from other IPD efforts as well; namely, that norms of collaboration were established early, and the management processes (pull planning) and technology (BIM field site kiosk) reinforced these collaborative norms.

As discussed further in the methodology section of this paper, this tenant improvement project included the build out of level 5 to house three departments. As the architect explains, this was an integrating challenge for the department units as well as the design and construction team: "*[this project] was not only integrated design and integrated delivery but also an integrated operational project that the client was bringing three different departments [together] that had operated as an independent customer in different management from each other: GI [Gastroenterology], interventional radiology and cardiac catheterization. There were a lot of similarities across the service lines [so] they could share resources and be more efficient with staffing and resources so they were bringing all these different service lines together in one location and in one management structure.*"

## LITERATURE

The fragmented approach of construction projects procurement and the delivery has negatively affected project effectiveness because it does not encourage integration, coordination and communication between project parties (Love et al 1998). Many suggest that to overcome the problems arising from this fragmentation the construction industry needs to move toward coordination of participants and more collaborative and integrated approaches to deliver more predictable results to clients (Egan 1998; 2002; Mitropoulos and Tatum 2000; Fairclough 2002; CMAA 2009). Scholars of high performance design, such as Orr (2006), have argued that professions of the built environment need to develop mastery of their own domain as well as develop shared mental models collaboratively. Bucciarelli (1994) defined "design as a social process" wherein teams define the problem and process then negotiate decisions across disciplinary constraints. In their work with integrated student teams in project based studios, (Dossick et. al., 2012) defined collaborative norms as the routines and practices, or social processes, students created around the day-to-day activities and the ways in which they co-created knowledge and shared mental models in a 10 week architecture, engineering and construction studio.

Existing literature describes an integrated project team as the case "where different disciplines or organizations with different goals, needs and cultures merge into a single cohesive and mutually supporting unit with collaborative alignment of processes and cultures" (Baiden et al 2006, pp 14). The degree of achieved integration for delivering a construction project is subject to Contractual, Organizational, and Technological mechanisms (Mitropoulos and Tatum 2000). Organizational cultures and norms on construction projects play important roles in how practices contribute to successful projects and that conflicting obligations of scope, company and project often impede successful inter-organizational collaboration (Dossick et al. 2009; Dossick and Neff 2010). The case study presented in this paper illustrates a process by which an IPD team developed norms of practice that allowed the team to discuss, negotiate and resolve conflicting obligations throughout the project process.

## CASE STUDY METHOD

The case study for this analysis was an Integrated Project Delivery (IPD) project to complete a tenant build-out, 24,500 square foot for Level 5 of the Jones Pavilion at Virginia Mason Hospital. The building that housed this new addition was part of a master plan expansion for the dense urban hospital in downtown Seattle that nests a new building together with older existing high-rise structures. The new building aligned with existing building level 5 and was an opportunity for the owner to reconfigure several procedural departments. The Core IPD team began design in January 2011 with a proactive design process over 4 months. The target cost process began in March 2011 and the team achieved the target cost of $16.5 million by August 2011. Construction occurred from October 2011 to May 2012. The core team, architect, general contractor and owner, signed an IPD contract, for form of which was specific to Virginia Mason. This IPD had a shared contingency pool that helped to align the business interests of the parties.

We selected this Virginia Mason case study for several reasons. First, it was a true IPD project with a tri-party agreement. The owner has used this delivery method before and has a mature process in place. Second, however, the owner was looking to work with a new team to get new ideas into their design and expand their lean construction processes, so the team was new to each other and new to the owner. This created an ideal case for studying how teams adopt and adapt integrated processes.

Data collection occurred in two phases. Members of the research team first conducted three job site tours during the construction phase of the project. They were particularly interested to study how integrated practices were impacting the execution of construction. In the first jobsite tour, representatives from the owner and designer were present and it was clear that the team was working well together (they finished each other's sentences and spoke about each other's work with knowledge and respect). The second and third jobsite tours focused on the contractor's work practices. To understand how the team created a successful collaborative culture, near the completion of construction, the research team conducted structured interviews with three architects, the general contractor's project manager and two project and field management personnel from the drywall subcontractor (see Table 1).

During the interviews, the research team had several objectives. First was to understand collaboration and integration, how these practices were established and what was done to integrate new project participants as they were joining the project, and how the integrated team atmosphere was reinforced throughout project execution. The second part of the interview focused on project standardization, which demonstrated how the Lean and BIM processes and tools were used to increase efficiency. In this paper, the focus is on the first part of the survey and the results of the integrated project process. What we found was that collaborative norms were established early, and were then reinforced through structured work sessions (such as production preparation process (3P) and pull-planning) as well as the use of a BIM kiosk on the job site.

Table 1. Some Project Participants Profile

| | **Owner: Virginia Mason (VM)** | **Architect: ZGF** | **General Contractor: Turner Construction** | **Subcontractor: Performance Contracting, Inc.** |
|---|---|---|---|---|
| **Previous work with owner** | Sought new design and construction partners | New to VM | New to VM | New to VM |
| **IPD-Lean experience** | Well established IPD and Lean | Well established Lean, Some IPD experience | Well established Lean and BIM, Some IPD | New to IPD, Lean and BIM |
| **Team members' Experience in healthcare projects** | Mature owner, many projects | Extensive healthcare experience | Some healthcare experience (hired for lean expertise) | Some healthcare experience |

## FINDINGS: COLLABORATIVE NORMS ESTABLISHED EARLY AND CONTINUOUSLY REINFORCED

Below are brief highlights to four main principles that were found to have established and reinforced collaborative norms among the integrated team in that project. First the proposal process established successful collaborative norms for the team. Then, the integrated team (3P) events reinforced these norms and extended them through the owner, architect and contractor organizational networks of stakeholders, (e.g., doctors and nurses), engineers and subcontractors. The pull planning sessions extended these collaborative norms into the construction phase, where new subcontractors were brought into the process. Finally, BIM kiosks functioned as a site for collaboration in the construction site, where interdisciplinary conversations would take place between the trades as well as with design and owner representatives. In this section, each of these four principles are presented.

**Proposal process established collaborative norms between architect and general contractor**

The proposal process was a unique from other qualifications based proposals, in that the Request for Proposal (RFP) was a one page document containing the Project Description, the goal "to create a state of the art integrated Procedural Center incorporating Virginia Mason Production System principles" and 4 improvement requirements including improvement of patient experience, decreased lead time, increased throughout and improved operator value-added time. The architect-contractor team submitted a written statement of qualifications and had a 2-hour workshop in which to demonstrate their proposed collaboration process. The presentation was open ended - not set list of things to cover. The owner was testing the teamwork and selected based on who the owner felt they wanted to work with and who was best fit for their team and their style. As a result, the architecture and general contractor team members established collaborative culture and norms that formed a basis for project work.

> *"[having the architect and contractor create a process submittal] was brilliant on Virginia Mason's part because it forced us to be collaborative in order to win the job together."* (contractor)

VM asked four joint architecture-contractor teams to create proposals for the tenant improvement project. According to the architect, "*[VM] were looking for partners that understood what they were trying to achieve but [with whom] they have never worked with before. And Turner never worked with them before, neither ZGf.*" VM used the selection process to find a team whom they felt they wanted to work with through this challenging operational integration process (integrating their three medical units). As the architect recalls:

> *"[four short listed] teams had to come and present their approach to this project and you got two hours to do it. They gave no framework structure to the interview; you had to engage them…. [In] two hours, you had to engage them in the process; the process that you might use to deliver the project, and engage them in a way that they participate and learn more about the project doing it. …[We] did it in an integrated way, architect and contractor together collaborating but also engaging them, pulling them in and saying hey: what are you looking for? what about this? have you thought about these issues? …"*

The architecture and construction team worked for 10 intensive weeks to prepare a proposal. This was a unique proposal for both teams. They were not given a specific program, just the goal of integrating the three operational units (GI, radiology and cardiac catheterization). Given almost no guideline, they came up with a strategy to both present the design issues and the integrated work process.

> *"....We kind of mapped out for them a project timeline for them and said here is how we engage various parts of the process... there is design and planning process, there was new construction planning process, there was energy and sustainability, there was construction management; we met all these. We were an integrated team. We told them how we bring in all these together at the right times and which decisions were needed."* (Architect)

The effect that this 10-week proposal process had on establishing team culture and collaborative norms for the project was remarkable. As the contractor explains in doing a job interview together, they realized cultural differences and differences in approaches: *" I have to tell you when [architects] are pitching together they really do [it] differently, and I've had the opportunity to pitch a lot of work so I was really surprised."* In our interviews, the architects and the contractor all mentioned the impact of the 10-week proposal preparation period. It appears that working through their different approaches to the proposal prepared the team to work together through the design and construction process by making each aware that they are going to be surprised by cultural differences, they should expect these differences, and the proposal process established norms of collaboration that accommodated for the negotiation and resolution of these differences. The contractor suggested that it *"really helped us align and bring the group together and I would say that [the proposal preparation] was the fundamental factor in ... the success of the project because it tied us together and then we were tied to the client."* Figure 1 illustrates the various times when key participants joined the integrated process and some of the collaborative tools that supported the integration process.

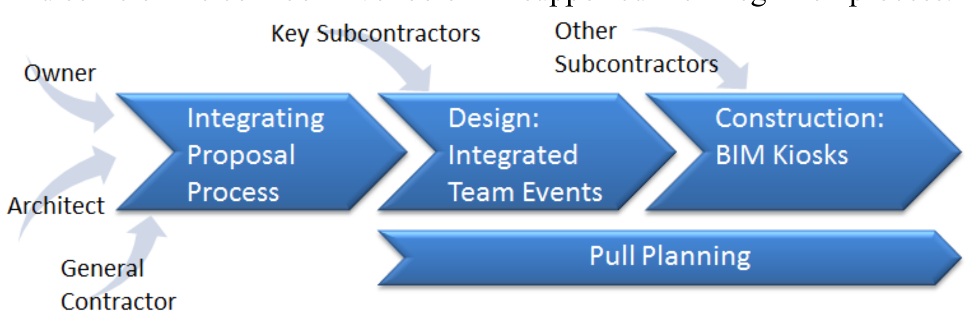


Figure 1. Example of Integrative Tools and First Engagement Times of Project Participants

**Integrated team (3P) events in the design phase extended collaborative norms established during the proposal**.

The design process was launched with a 3P event. This was a week long working session where the core team, architects, general contractor, and owner lead teams of stakeholders (e.g., doctors, nurses, staff, house keeping, operations), engineers, consultants and key subcontractors through the procedural processes for the "three separate service lines: GI, IR, and Cardiac Cath." They worked out how the 3 service lines would collocate, and sought to maximize patient and staff flow.

Subsequently, these same players reconvened to test design alternatives with physical mock-ups (Figure 2). For the operational alignment, *"[VM staff] conduct[ed] these week long events that bring together their clinical staff, their support staff, the design team, the construction team and they work through, from the beginning to the end. They are trying to get a vision of what their project is about."*(Architect) Through this process, the VM staff envisioned what they needed, designers created graphics (such as floor plans and renderings) and the construction team built plywood mock ups on the still empty 6th floor of the tower. For six months, the participants attended these monthly week-long events. Those we interviewed described these sessions with a lot of enthusiasm. This is where they really learned about the client and users.

Figure 2. Image from an Integrated Team (3P) event (obscured for anonymity)

Additionally, these meetings were where the users learned a lot about themselves. By the time the three departments were ready to move into the space, they already knew each other and had ownership in the design of their collocated work processes. These sessions were for them the essence of IPD, and provided an opportunity for each member to contribute their expertise to the problem at hand. One of the contractor's favorite images from the project is one that shows a doctor and a nurse standing with an architect and an electrical subcontractor inside a room mock up and discussing the location of wall outlets. It wasn't until the end users experienced the physical mockup space that they knew which design they wanted to proceed with. As one architect stated *"we were designing the space to support their process"*.

**During construction, the pull planning process reinforced collaborative norms through discussion of interdependencies and obligations.**

As the project transitions from design to construction, the emphasis shifts from design decision making to production. Although some of the major subcontractors such as electrical and mechanical were involved during design, the IPD team's challenge at this point was to bring on subcontractors who had not yet worked on the project. The pull planning process, which contributed to identifying constraints and improving planning reliability beforehand by collaborative planning, also contributed to team's integration process. The general contractor emphasized pull planning sessions as a way to integrate new subcontractors into the project and into the culture through information transparency. To a greater or lesser extent, this seemed to work fairly well. Although as the GC project manager noted that some of the subcontractors on the job *" ....and certain guys didn't know what to do. Like one of the contractors we brought in, he ended up, you know, the guy showed up the first day and he goes man this is how I always wanted to have this job and…he saw some of the pull planning we'd initially done and he did nothing from the day on. Nothing!",* others were enthusiastic to embrace the collaborative norms. As one subcontractor stated:

> *"So, once it started it never stopped. So, it moved from architect's office to the job site and then it moved to all the trades involved, the three majors, so we went right to pull planning from design....it was a work in progress and if we didn't get it done, we would talk about why, but more importantly, what we could do to get it done,"* (subcontractor)

**During field construction, the BIM kiosk extended the collaborative culture and the pull planning discussions into the field.**

For this project, Turner invested in field computer stations that contained models, drawings, RFIs and other project documents. For the subcontractor we interviewed, this had a great effect on their crew leadership. The foreman could stay on the jobsite with the crews (instead of in the field job trailers). The effect was that "*you don't have to wait for Wednesday's coordination meetings, or Wednesday's sub meetings. Pull-planning coordinates all you want right there on time on demand.*" (subcontractor interview) The kiosk became a site for conversation that extended the pull planning discussions.

> *"Mobile workstation takes that meeting or that location and puts it in the field available at all time and at any time because you maybe standing there looking at a detail and the mechanical guy comes over once to look at the detail and all of a sudden you start talking and coordinating. Again, an hour later, you maybe looking for something else and electrician may come over and start looking at something, looking at detail and you're*

> *communicating. So, instead of you being at your office and them being in their office, and them sending email, all of the sudden it puts [conversations] right there in the spot and available for anybody to coordinate it at any time."* (Subcontractor)

Once established throughout the project process, from proposal development, to design refinement to pull planning meetings, the collaborative norms flourished on the job site where BIM and other project documents were made available in the field where they were needed the most.

## CONCLUSION AND FUTURE WORK

First, this case study suggests that for this project team, it was instrumental to establish the integrated culture early. Second, this team also worked on reinforcing these collaborative norms and expectations throughout leveraging Lean processes and BIM tools. What became clear in this case study was the power that the proposal process had in establishing integrated collaborative norms for this team. The management of all team players actively engaged in reinforcing, building upon and maintaining integrated team culture and recognized the need to do so. For example, the contractor stated that "*The single most important thing that I did was focus on talking to the guys by their name and communicating with them.*" In the transition from design to construction, the team took on new members, subcontractors who had not participated in the intensely integrated design phase and had to be incorporated into the integrated culture. The general contractor's project manager used Pulled Planning and BIM kiosks to establish team processes and "sites" for conversation and emphasized the social processes of dialog and discussion as keys to project integration and development. This extended the integrated culture and prepared the field to collaborate more fully with the owner and design team. Time in meetings was considered productive and a vital part of the project.

Those interviewed for this project had strong leadership qualities: clear vision for what they wanted to achieve and guiding principles they applied to the chaos of every day work. A shared vision appears to be key for IPD success. As the contractor explained "*[VM] focused on the patient experience and patient safety, and that draws everybody in. So, they're incredibly aligned and they pull everybody else's alignment into that.*"

This project illustrates some guiding principles for those seeking to foster collaboration, be it on an IPD project or not. Providing processes and sites for dialog between project participants appears to have been instrumental in the successful team collaboration on this project. Furthermore, in the examples discussed in this paper the technologies used had affordances that supported dialog and interaction. The physical mock ups provided literal "rooms" for end users to interact with designers and builders, while the BIM Kiosk, as an information hub, created a meeting and interaction point on the jobsite for foremen to coordinate the detailed work of the day.

In this paper we have discussed the power of a clear and motivating owner vision, the success of establishing collaborative norms early in the proposal development, and how lean methods (such as design meetings, pull planning) and the BIM kiosk all reinforced and extended these collaborative norms throughout the project process. Future research opportunities include studying other cases, both IPD and non-IPD to understand how collaborative and cooperative norms develop and what strategies, tools, processes and technologies are instrumental in creating teaming outcomes.

## ACKNOWLEDGEMENTS

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# PREDICTING CONSTRUCTION DURATION WITH TYPICAL CONSTRUCTION SEQUENCES FOR HIGH-RISE BUILDINGS

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**Abstract:** Predicting construction duration is a challenging effort because construction schedules are dynamic and uncertain. Various studies have developed mathematical models to predict construction duration based on regression analysis, Monte Carlo method (MCM), and so forth. Yet regression analysis cannot capture duration uncertainties. Studies normally employ Monte Carlo methods to simulate hundreds to thousands of activities in a project schedule. This can be complicated, time-consuming and unrealistic because the statistical properties of all the activities cannot be readily determined in practice. This research first identified typical construction sequence(s) in condo building construction and then surveyed the statistical distributions of controlling activities on the sequence(s). Two-stage questionnaire surveys and goodness-of-fit statistical tests were conducted to achieve the above objectives. Subsequently a model for predicting the duration of building construction was proposed and applied to a high-rise building project. Results showed that the model reasonably predicts the construction duration for this apartment building. This research is beneficial for practitioners to estimate an overall construction schedule of building projects, especially in pre-construction phases.

**Keywords:** Scheduling; simulation; critical path method; Monte Carlo method; high-rise buildings.

## INTRODUCTION

The prediction of project time is a problem faced throughout the industries (McCrary et al. 2007), among them, forecasting construction duration plays a critical role in initial project phases (Stoy et al. 2007). A number of research efforts have been undertaken regarding project construction time forecasts, however the need for enhanced systems to provide reliable and repeatable project times still exists (Leach 2003).

The research aims at forecasting the probability of the construction duration for multistory apartment buildings. This research first identifies typical construction sequences and controlling activities in multistory building construction, and then develops time distribution functions for these controlling activities. The Monte Carlo method (MCM) is employed to model the uncertainty of construction duration, and an application will also be presented to simulate and estimate the construction time of a 25

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story apartment building. The direct application of this research is limited to apartment buildings from 10 to 30 floors using the bottom-up approach in Vietnam, however the approaches proposed in this research can be adopted to forecast project time for other project types and/or in other locations.

## RELATED WORK

The prediction of construction project duration has drawn various research efforts, however most of these efforts assume deterministic project duration. Regression analysis is typically used for project time forecasts. Perhaps Bromilow (1969) proposed the first empirical model for forecasting construction duration based on data from hundreds of construction projects collected in Australia. The Bromilow's time-cost (BTC) model is expressed in the form of $T = KC^B$ where T is the construction time in working days; C is the cost of the building in millions of dollars; K is a constant characteristic of building time performance; and B is a constant indicating the sensitivity of time to cost. The BTC model was adapted and applied to construction projects in other countries (Chan 1999; Ogunsemi and Jagboro 2006).

Many studies have extended the BTC model by either classifying projects before developing the BTC model or integrating more independent variables into project time prediction models. To achieve this studies normally employ single or multiple linear regressions. Before developing the BTC model Kaka and Price (1991) classified projects in four criteria; type of client, type of project, type of tender, and form of tender. Khosrowshahi and Kaka (1996) developed a regression model for estimating the duration of housing projects in the U.K. using a multivariate linear regression. In addition to project cost, project duration is a function of the other nine categorical variables including horizontal access, buildability and abnormality. Other studies (e.g., Chan and Kumaraswamy 1999; Hoffman et al. 2007; Irfan et al. 2011) also employed multiple linear regression to incorporate more independent variables into the project time forecast models.

A few project time prediction models attempt to account for project uncertainty. Critical Chain Scheduling (CCS) endeavors to add buffers to schedules to protect against uncertainties (McCrary et al. 2007), and PERT and the Critical Path Method (CPM) used with MCM or fuzzy logic are able to capture project uncertainty. Unfortunately, they have had limited use in practice (Besner and Hobbs 2006). This can be because a MCM of the detailed schedule with risks attached is often complicated and time consuming (AACEI 2011). Lee (2005) developed software called the Stochastic Project Scheduling Simulation to predict the probability of project completion. However, it requires a detailed schedule with uncertainty inputs and hence has the same limitation as mentioned above. Irfan et al. (2011) developed probabilistic models for project duration using the Weibull analysis. While the models may enhance the prediction of project durations, their implementation is probably hindered by difficulty in model building and use.

This research attempts to predict construction duration under uncertainty by integrating strengths of the previous project time estimation models. That is, the concept of a train of controlling activities in the template-based approach (McCrary et al. 2007) is adopted for identifying typical construction sequences in multistory building construction. The advantage of MCM in modeling uncertainty is that it can also be utilized after the typical construction sequences and controlling activities are identified from historically similar project types.

## RESEARCH METHODOLOGY

This research employs questionnaire surveys, case studies, and the Monte Carlo simulation. Each research method is used to fulfill different research objectives. The questionnaire survey was divided into two stages. Two questionnaires first obtained input from a few experts and then a pilot test was conducted before commencing the surveys. The first questionnaire was designed to collect data for identifying typical construction sequences in high-rise building construction, and were distributed to engineers and managers experienced in high-rise building construction from contractors in Vietnam. The first survey was analyzed to identify typically critical sequences and their controlling activities in building construction.

The second questionnaire was developed to survey durations of tasks on the critical construction sequences analyzed and identified in the first survey. Data from the second survey were analyzed to identify their statistical distributions. Kolmogorov-Smirnov goodness-of-fit tests were used to confirm whether the observed distribution for the survey sample conformed to typical distributions namely Normal, Beta, and/or Triangle distributions. Crystal Ball was also employed for distribution fitting and testing.

This research then applies the typical construction sequences from the two surveys to predict the construction duration of a twenty five story building project. The Monte Carlo simulation with the Crystal Ball software is employed to consider the uncertainties of the task durations.

## PREDICTING CONSTRUCTION DURATION FOR MULTISTORY APARTMENT BUILDINGS

### Typical Construction Sequences and Controlling Activities

Each construction project is unique therefore critical activities and critical paths are not the same in every one project. For the same type of construction projects, however, the critical path(s) might be similar. This research focuses on high-rise building projects where construction tends to be linear in the vertical direction, thus critical path(s), especially sequences of building construction and controlling activities, can be the same if similar construction methods and practices are employed.

Most apartment buildings in Vietnam have similar structures, facades, construction means and methods. The major structures of multistory apartment buildings in Vietnam are reinforced concrete frames and slabs. Architectural exterior and interior walls are brick with rendering and painting. Construction is bottom-up whereas the top-down approach may only be used for commercial and/or taller buildings with more basement floors. Formwork includes steel shoring, metal frames and pre-fabricated formwork panels which are made from plywood for the slabs or plywood reinforced by steel and/or aluminum frames for the columns and walls. Recently skytables for concrete slabs and climbing forms for concrete walls have been used but normally they are used for commercial and/or taller buildings.

This research concentrates on the common construction practices for multistory condo buildings as described above because these practices have been popular for years in Vietnam. Specifically, the focus is multistory apartment buildings with reinforced concrete frames and slabs, brick walls, traditional formwork systems, and bottom-up construction.

Typical critical path(s) were identified from the first questionnaire survey. Two major questions are used in this survey; question 1 is to identify critical and non-critical activities among the list of activities provided (Table 1) and question 2 helps identify the sequencing of the activities such as precedence and concurrence. A combination of these two questions resulted in typical construction sequence(s). For example, a response is (1) activity numbers 1, 2, 3, 4, 6 and 8 are critical for question 1 and (2) the construction sequence is 1 – 2 – 3.4.5 – 6 – 7 – 8 for question 2. The identified critical path is therefore 1 – 2 – 3.4 – 6 – 8. Sign "–" denotes an existence of precedence and non-concurrence while "." denotes overlapping and concurrence in general.

**Table 1.** Activity number and description

| Activity no. | Activity description | Activity no. | Activity description |
|---|---|---|---|
| 1 | Piling work | 9 | Painting |
| 2 | Substructure work | 10 | Lift installation |
| 3 | Superstructure work | 11 | Exterior glass wall, windows, and doors |
| 4 | Brickwork | 12 | Electrical system |
| 5 | Interior plastering | 13 | Plumbing system |
| 6 | Exterior plastering | 14 | A/C system |
| 7 | Waterproofing and tiling | 15 | Miscellaneous systems |
| 8 | MEP rough-in and ceiling installation | 16 | Other work |

Table 2 summarizes the results from the first survey which had thirty four responses received from the sixty questionnaires distributed, making the response rate 57%. In terms of the number of years experienced in building construction, respondents consisted of ten or more (23%), between five and ten (45%), and less than five (32%). The first three activities of the critical construction sequences (Table 2) are the same (activity numbers 1, 2, and 3), except for path number 5, where the activity 16 of "other work" appears in the paths as the last activity. The sequencing of the remaining activities in the middle of the paths is generally different. The computation will be extensive and time consuming if all paths are considered, therefore these remaining middle activities are combined in one major activity called "finishing." This combination is in accordance with the two basic activity combinations of sequences of activities and parallel activities (AACEI 2012). In reality, finishing work of apartment building projects includes both the exterior and the interior while that of other projects only includes the exterior finishing because customers would complete the interior finish themselves. The construction sequence of multistory apartment buildings is one of the two critical trains: (1) Piling – substructure – superstructure – exterior/interior finishing – other work and (2) Piling – substructure – superstructure – exterior finishing – other work. Overlapping may occur between these activities. Similarly to the template-based approach, the activities on the critical trains will be called controlling activities.

**Table 2.** Frequently identified critical paths

| No. | Critical construction sequences | Frequency | Percentage |
|---|---|---|---|
| 1 | 1 – 2 – 3 – 4.5.7 – 9 – 11 – 16 | 7 | 20.6 |
| 2 | 1 – 2 – 3 – 4.5.6 – 9 – 7 – 16 | 5 | 14.7 |
| 3 | 1 – 2 – 3 – 4.5 – 9.7 – 11 – 16 | 5 | 14.7 |
| 4 | 1 – 2 – 3 – 4.5 – 6.9 – 16 | 4 | 11.7 |
| 5 | 1 – 2 – 3 – 4.5.6.7 – 9.10 | 3 | 8.8 |
| 6 | 1 – 2 – 3 – 4.5.6 – 7 – 9 – 16 | 2 | 5.9 |
| 7 | 1 – 2 – 3 – 4.5 – 6.7.9.10 – 16 | 2 | 5.9 |
| ... | ... | … | … |
| | **Total** | **34** | **100** |

**The Statistical Distributions of the Controlling Activities**

The next step of this research is to investigate the statistical distributions of the activities on the construction sequences identified in the previous step. Activity durations are uncertain and overlapping between the above activities may also be uncertain. As a result of this uncertainty the construction duration cannot be predicted if only the activity durations on the construction sequence are known, therefore instead of investigating the statistical distribution of a certain activity as a whole, this research only investigates the distribution of the non-overlapping part of an activity compared to the preceding activity. For example, activity B partially overlaps activity A which is activity B's predecessor. This research only investigates the duration distribution of activity B right after activity A finishes; the duration in the distribution does not include the overlap with activity A.

The second survey was conducted to investigate the statistical distributions of controlling activity durations considering only non-overlapping parts. For example, with regard to superstructure work the respondents were asked how long the superstructure work took to finish after the substructure work was finished in their recent apartment building projects. Sixty questionnaires were sent to the same pool of respondents in the first survey, and thirty-one responses were received with a response rate of 52%. The type of foundation in these projects was reinforced concrete (RC) pressed piles. For piling activity this research only investigates the duration distribution of the RC pile pressing; other foundation types such as bored piling are not in scope of this research.

Activity durations depend on many factors, especially project scale (project cost, floor area, perimeter, number of floors etc). Therefore this research first develops the distribution of unit activity duration to cancel out the effect of project scale across 31 projects investigated in the second survey. One or more parameters are chosen for each task to make the unit in the distribution is day/chosen parameter's unit, instead of day or month. The selected parameters must be the best representative for the activity and make the distribution unit independent from the project scale. The duration of the RC pile pressing depends on geotechnical conditions, pile length and load, piling area, building height, the number of pressing equipment etc. It is time consuming and complicated if all those parameters are taken into consideration, thus this research chooses total floor area in square meters as a single representative factor for the RC pile pressing. The total floor area (i.e., floor area times the number of floors) may account for parameters such as piling area, pile length and load, and building height. The unit of duration distribution for the RC pile pressing is day/m2/pressing rig (Table 3). The duration of substructure work depends on foundation type, basement area, and the number of basement levels. The total basement area (the number of basement levels times basement area) is selected as the representative factor. Similarly, it is reasonable to choose total area of floors from the ground as the representative factor for superstructure work.

The principle for choosing representative factors for interior/exterior finishing and exterior finishing is similar. The duration of exterior finishing depends on the façade area, which is the product of the floor perimeter, floor height, and the number of floors from the ground. Because the floor height is generally the same from floor to floor, the total perimeter of floors from the ground (i.e. floor perimeter times the number of floors from the ground) is a reasonably representative factor for the exterior finishing work. The duration of the interior/exterior finishing is contingent on engineering systems, the total floor area, the building façade area etc. This research chooses the product of the total floor area and the total perimeter of floors from ground as a representative factor for this task. The total floor area represents the interior finishing while total perimeter represents the exterior finishing as discussed above. Finally, "other work" may include miscellaneous activities such as punch-list items, testing and commissioning. It is difficult to establish a representative factor for this task. This research chooses a percentage of the total duration of all preceding tasks (RC pile pressing, substructure, superstructure, and finishing) when developing statistical distribution for the duration of "other work."

With the representative factors selected for each task, statistical distributions of activity duration can be established using the Kolmogorov-Smirnov goodness-of-fit tests in the Crystal Ball. Activity durations from responses are first converted to respective units described above before conducting a statistical analysis. A data set may fit many distributions therefore this research only assesses Normal, Beta, and Triangular distributions. These distribution functions are widely observed in construction and used in construction research (AbouRizk and Halpin 1992; Lee 2005). The goodness-of-fit tests indicate that all the controlling activities fit these three distribution functions. Due to paper length limit, Table 3 only presents the parameters of the Normal distributions for the six tasks.

**Table 3.** Distribution parameters of controlling activities

| Task | Unit description | Unit | Normal μ | Normal σ |
|---|---|---|---|---|
| RC pile pressing | Duration/Total floor area | $10^{-3}$day/m$^2$/ pressing rig | 4.23 | 0.82 |
| Substructure | Duration/Total basement area | $10^{-3}$ day/m$^2$ | 22.46 | 3.34 |
| Superstructure | Duration/Total floor area from ground | $10^{-3}$ day/m$^2$ | 11.04 | 2.42 |
| Interior/exterior finishing | Duration/Total floor area * Total perimeter of floors | $10^{-6}$ day/(m$^2$x m) | 1.93 | 0.28 |
| Exterior finishing | Duration/Total perimeter of floors | $10^{-3}$ day /m | 43.68 | 5.95 |
| Other work | Percent | % | 4.74 | 1.23 |

Many simulation scenarios take place because durations of the controlling activities can follow various types of distribution functions, Normal, Beta, and Triangle, therefore the simulation should allow for choosing any of these distribution functions for each controlling activity. As a result, 243 combinations exist from five controlling activities in any of the two critical trains and three distribution functions for each activity in this simulation. The first simulation combination, named Case 001, is when all five controlling activities follow a Normal distribution. The last combination, Case 243, is when all five controlling activities follow a Triangular distribution.

A simple Excel spreadsheet with the Crystal Ball add-on was developed to simulate construction duration for apartment buildings with distribution parameters identified for the controlling activities. To estimate the construction time for a given project, project information (basement area, typical floor area, number of floors, numbers of basement levels etc.) are required as input for the simulation. For a better illustration of application, this paper presents duration simulation in the following case study.

## APPLICATION TO A CASE STUDY

### Description of the Case Study

The case study was an apartment complex located in Ho Chi Minh City, Vietnam. It consisted of two basement floors, five podium floors, and twenty standard floors which were separated in two identical blocks. The owner used the traditional procurement approach of design-bid-build. The foundation was constructed of RC concrete piles and was installed by the pressing method. The major structural system was reinforced concrete, including columns, shear walls, beams, and slabs. Interior and exterior partitions were rendered and painted brick walls. The areas of basement, podium, and typical floors were 5000, 4800, and 1550 $m^2$, respectively. The perimeters of basement, podium, and typical floors were 280, 270, and 150 m, respectively.

The general contract included all construction work, civil and structure (C&S), MEP, and a full finish. Many packages from the scope of work were subcontracted such as piling, MEP, lifts, doors, and windows. Construction means and methods followed the common practices used for apartment buildings in Vietnam as described above. The project was substantially completed after 37 months of construction from October 2006 to November 2009 – ahead of schedule by one and a half months. The next section describes the simulation and estimation of the construction duration for this project to verify the construction time forecast model.

**Construction Duration Simulation and Discussion**

The case project is within boundary of the proposed construction duration simulation. Because the contract required a full finish (both interior and exterior), the first critical train including five controlling activities of piling, substructure, superstructure, exterior/interior finishing and other work is used to simulate and estimate the construction duration for this apartment building. Because of a large project site it was divided into two equal construction zones which were concurrently performed by separate construction teams. In the top twenty floors the two construction zones were the two blocks. The two zones were in vertical parallel construction therefore project data from one zone was the input for estimating the construction duration. The project information (i.e., numbers of basement floors, numbers of standard floors, the basement floor area etc) is entered into the developed Excel spreadsheet with the Crystal Ball add-on, and 10,000 Monte Carlo simulation trials were run.

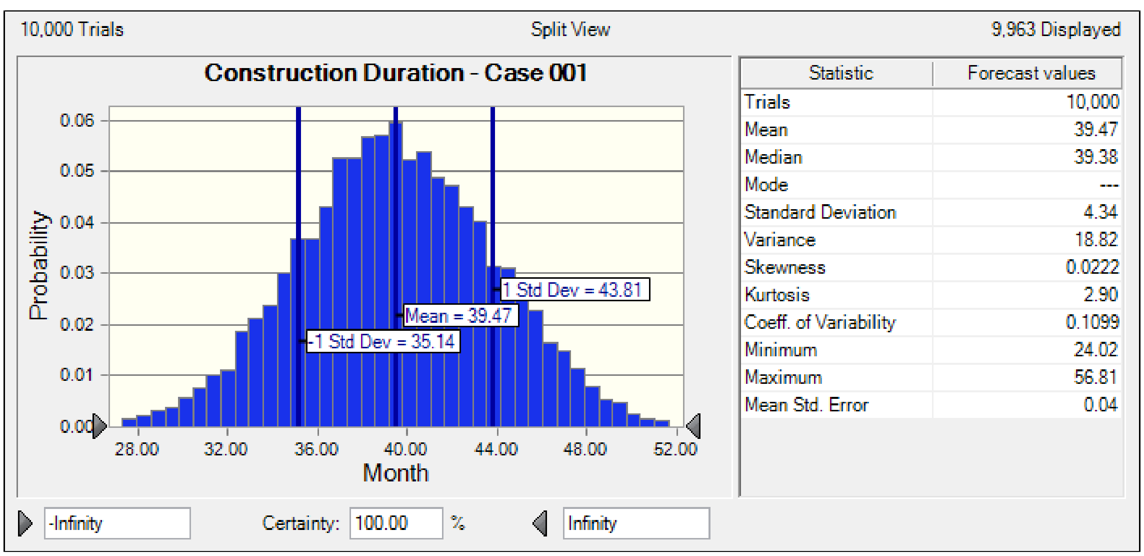


**Fig. 2.** Construction duration with normally distributed controlling activities (Case 001)

Fig. 2 demonstrates the simulation results of the construction duration when all five controlling activities are normally distributed (Case 001). The construction time also looks to be of Normal distribution, and the mean and standard deviation of the duration are 39.5 and 4.3 months respectively. In extreme scenarios, the project could be completed as early as 24.0 months or as late as 56.8 months. These results show that the simulation model reasonably forecasts the construction duration of this project. The actual construction duration (37 months) is within plus/minus one standard deviation of the mean (35.2 – 43.8 months).

The distributions of the construction durations in the remaining combinations (Case 002 to Case 243), not presented in this paper, have similar results. This indicates that the different distribution functions of the controlling activities and their combinations do not significantly affect the distribution of the simulated construction duration in terms of shape and spread. The mean and standard deviation of the simulated construction duration does not vary considerably among 243 combinations, therefore although the duration of the controlling activities can statistically fit many distribution functions, one may choose one or a few distribution functions for each activity without compromising the ability of capturing the variability and uncertainty of the overall construction duration. This makes the simulation and estimation of the construction time less complicated and time consuming, therefore the project time forecast model which integrates the template-based approach and the Monte Carlo simulation as proposed in the current research is more practical and applicable in the construction industry.

## CONCLUSION

The construction time forecast model in this research takes the advantages of the template-based approach and the Monte Carlo simulation. This research first identified typical construction sequence(s) and their controlling tasks in apartment building construction and then surveyed the statistical distributions of the controlling tasks. Two-stage questionnaire surveys for the experienced professionals and goodness-of-fit statistical tests were conducted to achieve the above objectives. Subsequently a model for predicting the construction duration was proposed for multistory apartment buildings. The model is limited to typical multistory apartment buildings which have reinforced concrete frames and slabs, bottom-up construction, and the common formwork system.

The model is applied to simulate and estimate the construction time of a 25-story apartment building. The results show that the simulation model reasonably forecasts the construction duration of this project. The actual construction time is within plus/minus one standard deviation of the mean of the simulated construction duration. The case study also revealed that one may choose only one or a few distribution functions for each controlling activity without compromising the ability of capturing the variability and uncertainty of the overall construction duration, although the duration of the controlling activities can statistically fit many distribution functions. This further makes the simulation and estimation of the construction time less complicated and time consuming, and in turn the project time forecast model proposed in this research can be more practical and applicable in the construction industry.

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# ASSESSMENT OF EFFECTIVENESS OF PLANNING TECHNIQUES AND TOOLS ON CONSTRUCTION PROJECTS IN LAGOS STATE, NIGERIA

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## ABSTRACT

Construction project planning is an essential element in the management and execution of construction projects which involves the definition of work tasks and their interactions, as well as the assessment of required resources and expected activity durations. The study therefore examined the awareness of professionals in construction industry of the various types of planning techniques and tools used on construction sites, assessed the effectiveness of planning techniques and tools used on selected construction sites in Lagos State, Nigeria, and identified the factors affecting the choice of planning techniques and tools towards effective and efficient delivery of projects. Questionnaires were administered on selected building professionals (Project Managers, Engineers, Architects), and Contractors and Sub-contractors directly involved in construction work on sites in Lagos State with emphasis placed on planning and the use of planning tools and techniques as major tools for successful project execution. The data obtained were analyzed using the Statistical Package for Social Scientist for Windows (SPSS), and the results were presented by the use of statistical tools such as frequency tables and pie charts. The study shows that there is low awareness on the functional use of construction planning tools and techniques, and recommended that the use of the construction planning tools and techniques should be applied in all building projects and there should be regular adequate training of professionals on the effectiveness and improvement in Information Technology in the construction industry especially in project planning and execution.

Keywords:

Construction, planning techniques, planning tools, projects

# 1.1 INTRODUCTION

Construction projects require adequate planning for them to be successful because of the numerous materials, plants and equipment, parties, several stages and activities and complex methods that are involved. Mawdesley (2001) maintained that the numerous activities or operations and parties, constraints such as time and cost involved in a construction project necessitates careful and proper planning before the start of work. Sadly to some professionals in the construction industry, planning has lost some of its effectiveness due to their regular unsuccessfulness in managing project change, including project delivering to time and cost. It has been observed that during some construction of projects in Nigeria, there are a lot of activities being carried out adhoc but without any direction, planning or proper organization. Such disorganization leads to the rise of a lot of problems arising such as construction delays, cost overrun, waste of materials and many more. Although there are other factors such as insufficient finance, lack of effective equipment, delivery delay process due to traffic, hoodlums, dishonesty (corruption) etc. which may affect project delivery but when examined properly some of this outside factors can be avoided with proper planning. Planning techniques and tools are either not commonly or effectively used in construction sites in Nigeria. This study therefore aimed at investigating the awareness of construction professionals in the adoption of planning techniques/ tools on construction sites and their effectiveness on construction projects.

## 2.1 RELATED STUDIES ON PROJECT PLANNING AND TOOLS

Construction project planning is an essential element in the management and execution of construction projects. It involves the definition of work tasks and their interactions, as well as the assessment of required resources (plant, material and labour) and expected activity durations. Hendrickson (2008) mentioned that in developing a construction plan, it is common to adopt a primary emphasis on either cost control or on schedule control because construction planning is cost or expense oriented. Construction planning involves planning time, resources and implementation (Chitkara, 2008). Moreover, Project Planning is one of the major components required to attain an effective project control. There is a range of Planning methods and techniques used for project control or management such as Bar Chart, Critical Path Method (CPM), Performance Evaluation and Review Technique (PERT) and Earned Value Management (EVM) as well as a range of risk and change management procedures and types of analysis. There are also increasingly sophisticated computer applications such as project management systems to help model both time and cost, which can now be linked with CAD tools thus enabling the linking of building elements to create 4D and 5D models. Project planning has been found to be one of the most significant factors for the efficient and effective delivery of projects (Arditi, 1985; Clayton, 1989; Syal *et al,* 1992). Project planning also provides the capability to reveal trends toward cost overrun and/or schedule slippage. Identifying those trends early enables more successful project management and reduced risk.

However, Frank and McCoffer (2001) emphasized that planning at both strategic and operational levels for a construction project employs various tools and techniques to help the planner to achieve optimization for the decision involve. Jon, Allen, Wickwire, Driscoll, Hurlbut*, (*2002) mentioned that one of the key decisions to be made before a project begins is which scheduling method is best suited to the project. Regardless of the scheduling system chosen, the owner or the owner's agent responsible for managing the project should have experience with the scheduling method selected (Tat, 2009). Frequently, the owner and the designer decide on scheduling requirements as a part of the planning process for a project (Jon *et. al.* 2002). Tat (2009) stated that the major purpose of construction schedule is to map out the progress expected on a construction project in a timeline that is most efficient and cost effective possible. It serves as a base plan for any changes that might have to be made due to unforeseen circumstances, unexpected delays, or owner changes and additions. When coupled with communication and project management software, it is an effective, efficient way to track progress, and flag trouble spots before they become critical. After project completion, it can serve as a guide in future projects through post-completion analysis.

Twomey (2006) emphasized that the key factors in keeping a project on track are to understand what causes delays and then to properly plan and manage schedule issues before they become problems. Delays of individual construction tasks may not be preventable but those that can't be avoided do not necessarily have to hold up the entire project. The success of any construction project is based on balancing the resources of cost, quality, and schedule. All three of these issues are important. On many projects, however, time is the most critical issue for the overall success of the plan. Furthermore, Jon *et. al.*(2002) said that as many contractors lack the skills necessary for successful scheduling, but the client may choose to instead to provide successful scheduling consultant for the contractor and may even pay for this service. The participation of key subcontractors and suppliers to the development of a workable plan (detailed activity plans) is emphasized by Claugh and Sears (2000). Whereas, Mohammed *et. Al*, (2006), believed that four areas should be properly investigated prior to the development of the project planning procedures. The critical areas that have been identified are process of acceptance, responsibilities of contracting parties, application of work schedule, and implications of work schedule. Many of the key problems of implementation lie in the general environment of the project and not under the direct control of the project (Tat 2009)**.**

It should be noted that there are some planning tools that help improve project delivery by making use of recent works and visions for construction. IT researches are gearing towards the accomplishment of innovative communication and information management using model driven, life cycle thinking, internet-based, simulation, and visualization strategies (Gudnasson ,2000; Sarshar et al. 2000; Amor and Betts 2001). Examples of these are a central project model that facilitated the co-ordination, exchange, and sharing of project information from a web-based repository and the use of 4D CAD and virtual reality for construction product/process simulation and visualization throughout the project life cycle. .
The recent Planning Tools Software include Lewis Framework**-** a prototype called "LEWIS – Lean Enterprise Web-based Information System for Construction" In this case, the supportive organizations can be informed of the current project status and

requirements at the work face in real time (Eknarin and Nashwan, 2002). Others are **3D CAD, 4D CAD,** 4D models that are effective tools for communicating schedule and scope information (John and Martin, 2001). 3D and 4D models are used as communication tools to share project information with all project participants including architects, engineers, the general contractor, subcontractors, and the owner (John and Martin, 2001). 4D models can also be used for Schedule creation, Schedule analysis, Communication and Team building:

**Primavera-**Primavera P6 (was P5, now P6 v7.0) is a project management software package that is used for managing and control project related activities. Resources representing labour, materials and equipment are used to track time and costs for the project;

**Building Information Modelling (BIM) is** basically the same as Building Product Model, which is the process of generating and managing building data during its life cycle. Building Information Modelling (BIM) has become a valuable tool in some sectors of the capital facilities industry (Harris, 2007).

**Planisware 5-** (formerly known as OPX2) is Planisware primary software solution for Project Management and Project Portfolio Management. Planisware 5 supports five functional areas namely Project Management (Cost, Resource, Planning), Project Portfolio Management, Idea Management, Business Intelligence (Road mapping, simulation, scorecards), Collaboration and time tracking; WorkPLAN ERP products allow companies or departments to automate and manage the most important activities such as project costs, quotations, orders, planning, document management, analysis of 3D CAD files, bills of materials, quality, touch screen to control time and attendance and to record time spent on tasks, purchasing, stock management, key performance indicators, management overview and strategic analysis;

**Oracle Project** is a comprehensive set of solutions that can help predict and successfully deliver global projects by integrating, managing, and providing insight into enterprise project information. Oracle Project Management provides project managers the visibility and control they need to deliver their projects successfully. All elements of the project lifecycle including planning budgets and forecasting costs and revenue, managing issues and change requests, and managing project performance, are integrated and stored in one repository, enabling project managers to operate more efficiently and effectively. Oracle Project Management is an integrated part of Oracle Projects. Oracle Project Management provides an integrated solution to enable consultants manage projects to ensure successful deliveries with less effort. From setup to closure, one can have access to tools to view the health of their projects, can gather information quickly, and create a work plan. Oracle Project Management captures task schedule and baseline dates as well as dependencies (finish-to-start, start-to-start, finish-to-finish, and start-to-finish) within and across projects.

## 3.1 METHODOLOGY

A total of sixty questionnaires were distributed to selected building professionals in different construction sites in Lagos State with emphasis on placed on planning and the use of planning tools and techniques as major tools for successful project execution and forty questionnaires were returned.(See Table1).The Ranking Method and Simple Percentage were used in the analyzing the data. The Ranking Method was used to rank the major possible factors affecting the choice and effective use of these planning tools and techniques. Ranking method is a simple statistical method where subjects are ranked according to some specified criteria or an operationally defined characteristic or property.

In using **ranking method**, the following formula was used:

Relative Index (R.I) = S/xn

Where,

R.I = Relative index which ranges between 0-1.

S = Rank sum. = $\sum$ n W

W = corresponding weight (score) of rank category (1 to 4)

x= no. of weighed characteristics.

n= no. of respondents.The subject or factor with the highest R.I is the first in rank order.

**Simple Percentage**

The simple percentage is calculated using the formula:

x/n X 100%

Where,

x= no. of observations in each question.

n= total no. of observations in each question.

### 3.2 DATA PRESENTATION, ANALYSIS AND DISCUSSION OF FINDINGS

The data obtained were analyzed using the Statistical Package for Social Scientist for Windows (SPSS), and the results were presented by the use of statistical tools such as frequency tables and pie charts. A total of sixty questionnaires were distributed to different professionals in different construction sites in Lagos State and forty questionnaires were returned. (See Table1).

### 3.2.1: Respondents Characteristics

The characteristics of the respondents are shown in Table1

Table1 **Respondents Characteristics**

| S/N | Respondent | Questionnaires distributed | Questionnaires returned | Percentage returned % |
|---|---|---|---|---|
| 1 | Architects | 10 | 7 | 70 |
| 2 | Builders | 10 | 9 | 90 |
| 3 | Civil Engineers | 10 | 8 | 80 |
| 4 | Project Managers | 10 | 6 | 60 |
| 5 | Others | 20 | 10 | 50 |
| | Total | 60 | 40 | 66.7 |

Table1 shows that 70% of the architects returned the questionnaires, 90% and 80% responses from the builders and civil engineers respectively. The average total is 66.7%. This is a very high response.

Furthermore, most of the respondents are highly qualified educationally because nine (22.5%) respondents have at least HND, thirty (30.0%) respondents have BSc, and nineteen (47.5%) respondents have M.Sc and higher qualifications. Fourteen (35%) of the respondents have more than ten years of working experience in the construction industry and twenty three (57.5%) have more than twenty years of experience. It can therefore be assumed that the respondents have good understanding of construction processes.

### 3.2.2. Value of the projects executed by respondents

The projects being executed by the respondents vary from one million naira to 1billion naira as tabulated in Table4.

**Table 2: Value of the projects executed by respondents**

| S/N | Contract Sum | Frequency | Percent |
|---|---|---|---|
| 1 | 1 - 100 million | 12 | 30.0 |
| 2 | 101 - 250 million | 10 | 25.0 |
| 3 | 251 - 500 million | 9 | 22.5 |

| | | | |
|---|---|---|---|
| 4 | 501 - 1 billion | 8 | 20.0 |
| 5 | 1 billion above | 1 | 2.5 |
| | Total | 40 | 100.0 |

Table 2 shows the value of the projects executed by the respondents. Most of the projects executed by the respondents were higher than N100million in contract sum because most of the projects were residential housing estates (See Figure 1).

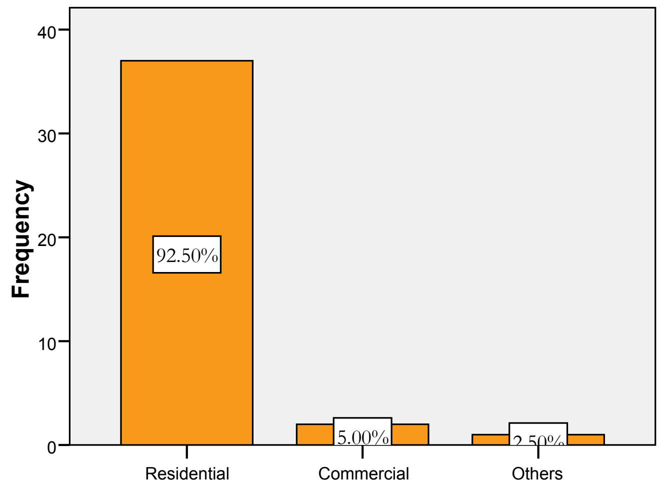


Figure 1: **Type of Project**

Figure 1 shows that 92.5% of the project sites surveyed are residential sites, 5% are commercial and 2.5% are for other sites including industrial and religious.

### 3.2.3. Planning Techniques used in executing projects

The ranking of planning techniques used in executing projects executed by respondents is shown in Table4

**Table 3: Ranking of Planning Technique used in executing projects**

| S/N | Planning Technique | Frequency % | Rank |
|---|---|---|---|
| 1 | Bar Chart (Gantt Chart) | 97.5 | 1 |
| 2 | Critical Path Method (CPM) | 85 | 2 |
| 3 | Visualization Using 2D, 3D Cad And 4D Simulation Clips. | 65 | 3 |
| 4 | Pert Chart | 56 | 4 |

| | | | |
|---|---|---|---|
| 5 | Line Of Balance | 45 | 5 |
| 6 | Gert Chart | 45 | 6 |
| 7 | Earned Value Management (EVM) | 23.5 | 7 |
| 8 | Q Scheduling | 12.5 | 8 |
| 9 | Lean Construction Technique | 8.5 | 9 |
| 10 | Lewis Method | 5.5 | 10 |
| 11 | Earned Value Analysis (EVA) | 4.6 | 11 |

Table 3 shows that Bar Chart (Gantt Chart) is the most commonly used planning technique while Earned Value Analysis (EVA) is the least commonly used planning technique.

### 3.2.4: The Factors Affecting the Effective Use of Planning Techniques.

The Factors Affecting the Effective Use of Planning Techniques by the respondents is shown in Table 4.

**Table4: The Factors Affecting the Effective Use of Planning Techniques**

| S/N | Factors affecting effective use of planning techniques. | 4 | 3 | 2 | 1 | S =∑nW | R.I | Rank |
|---|---|---|---|---|---|---|---|---|
| 1 | Lack of Technical Know-how knowledge | 25 | 9 | 3 | 2 | 135 | 0.86 | 1st |
| 2 | Lack of detailed project design information | 13 | 20 | 5 | - | 127 | 0.84 | 2nd |
| 3 | Poor management skills | 17 | 18 | 3 | - | 128 | 0.84 | 2nd |
| 4 | Insufficient finance | 14 | 21 | 2 | - | 123 | 0.83 | 3rd |
| 5 | Lack of personnel (Man-power) | 16 | 18 | 3 | 1 | 125 | 0.82 | 4th |
| 6 | Lack of Availability of machinery | 10 | 22 | 4 | 1 | 117 | 0.79 | 5th |
| 7 | Execution and implementation of the planned schedule | 9 | 23 | 5 | 1 | 116 | 0.76 | 6th |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| 8 | Climate and Weather effects | 7 | 21 | 7 | 2 | 107 | 0.72 | 7th |
| 9 | Inadequacy of work-force executions | 8 | 18 | 9 | 3 | 107 | 0.70 | 8th |

Table 4 shows Lack of Technical Know-how knowledge as the most important factor affecting the use of planning techniques while inadequacy while inadequacy of work-force execution is the least factor.

### 3.2.5: Planning Tools used in executing projects

The ranking of the awareness of planning tools used in executing projects by the respondents is shown in Table 5.

**Table 5: Ranking of Planning Tools used in executing projects**

| S/N | Planning Tools | Awareness % | Rank |
|---|---|---|---|
| 1 | Microsoft Project | 85.2 | 1 |
| 2 | Microsoft Office Project Server | 80.5 | 2 |
| 3 | 2D And 3 D Cad (Rivet) | 76.5 | 3 |
| 4 | Primavera Project Planner | 65.2 | 4 |
| 5 | Building Information Model(BIM) | 34.5 | 5 |
| 6 | E- Estimating | 31.5 | 6 |
| 7 | Plan VIEW | 22.6 | 7 |
| 8 | Oracle Project | 12.7 | 8 |
| 9 | 4D Simulation Clips | 10.4 | 9 |
| 10 | WorkPLAN Enterprise | 3.6 | 10 |
| 11 | Planisware 5 | 2.6 | 11 |

Table 5 shows the response rate of the respondents towards the different planning tools, stating their awareness of the tools, and how frequently the tools are used on construction sites. The most commonly used tool is Microsoft Project because of its major awareness while the least commonly used is Planisware 5 because of lack of its awareness.

### 3.2.6: Challenges of Planning In Construction Sites

The Ranking of the challenges Of Planning in executing projects on Construction Sites based on the Relative Index is shown in Table 6.

**Table 6: Ranking of Challenges of Planning in Executing Projects on Construction Sites.**

| S/N | Challenges Of Planning In Construction Sites. | 4 | 3 | 2 | 1 | S =∑nW | R.I | Rank |
|---|---|---|---|---|---|---|---|---|
| 1 | Climate and Weather effects | 18 | 19 | 2 | - | 133 | 0.85 | 1st |
| 2 | Poor management skills | 17 | 16 | 4 | 1 | 125 | 0.82 | 2nd |
| 3 | Lack of Technical Know-how knowledge | 11 | 24 | 2 | - | 118 | 0.79 | 3rd |
| 4 | Difficulty in plan evaluation | 10 | 23 | 4 | 1 | 118 | 0.79 | 3rd |
| 5 | Inability to set realistic completion dates | 13 | 18 | 5 | 1 | 117 | 0.79 | 3rd |
| 6 | Inability to cope with non-precedence constraints | 6 | 23 | 2 | - | 97 | 0.78 | 4th |
| 7 | Difficulty in plan communication | 9 | 21 | 6 | - | 111 | 0.77 | 5th |
| 8 | Inadequate report for analysis of constraints at operational level | 8 | 21 | 5 | 2 | 107 | 0.74 | 6th |
| 9 | Inability to measure progress achieved against program objectives | 8 | 20 | 9 | 1 | 112 | 0.73 | 7th |
| 10 | No appraisal of the validity of existing plans in terms of meeting program objectives | 10 | 13 | 9 | 2 | 99 | 0.73 | 7th |
| 11 | Inadequacy for work-force executions | 10 | 19 | 6 | - | 109 | 0.49 | 8th |

Table 6 shows the ranking of the challenges of planning in construction sites .Climate and Weather is the major factor affecting planning on construction site, Poor Management Skills is second, Lack of Technical Know-how knowledge is ranked third, Difficulty in plan evaluation is ranked forth, Inability to set realistic completion dates is ranked fifth. These are the main the Challenges of Planning in Construction Sites.

The implication of findings is that there is low awareness of the planning tools among the respondents and this affects the frequency of their usage in project execution. The challenges of planning in executing projects on construction sites vary from climate and weather effects to inadequacy of workforce for execution. Poor Management Skills, Lack of Technical Know-how knowledge and Difficulty in plan evaluation are factors that require most urgent attention for prompt and efficient delivery of projects.

## 4.1 CONCLUSION

The study showed that bar charts, critical path networks, visualization using simulation clips and probabilistic pert analysis are the most known and used technique on sites. The main tools used in planning are Microsoft office project server, Microsoft project, 2D and 3D cad (rivet). The main factors that determine the choice of planning techniques are the size of project, awareness of these planning techniques and skills in using them. The five (5) main Challenges of Planning in Construction Sites are; The Climate and Weather effects, Poor management skills, Lack of Technical Know-how knowledge, Inability to set realistic completion dates and Difficulty in plan evaluation. It concluded that planning techniques and tools are not adequately utilized because of lack of awareness and lack of technical knowhow. It therefore recommended that the use of the construction planning tools and techniques should be furthered be encouraged in all building projects and there should be regular adequate training of professionals on the effectiveness and improvement in Information Technology in the construction industry especially in project planning and execution.

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# COMPARATIVE STUDY OF ENERGY EFFICIENCY OF GLAZING SYSTEMS FOR RESIDENTIAL AND COMMERCIAL BUILDINGS

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**ABSTRACT :**

The 2011 Building Energy Databook (DOE, 2011) reported that buildings use approximately 40% of the nation's total energy use. One method of reducing this value is to replace inefficient single glazed window units with their newer, energy efficient counterparts. This study involved the investigation of several different glazing solutions. A comparative energy investigation of numerous products on the market was performed using multiple different software packages for a model residential and commercial building in five different climates across the United States. The paper will introduce the advanced glazing technologies used in the study, present the details of the selected residential and commercial buildings modeled for energy analysis, discuss the results of the thermal property evaluation and energy analysis, and present the conclusions derived from the study.

**Keywords:** Building Envelope Systems, Glazing, Energy Efficiency in Buildings, Building Retrofits

## INTRODUCTION

In recent years, there have been several factors that have led our society to pursue improved energy standards. Among these are global climate change, overdependence on fossil fuels, and rising costs associated with energy use. The efforts to improve our energy consumption are currently taking place on several different fronts. Automobile manufacturers are working to develop more fuel efficient cars. Alternative fuel sources, some of which are more efficient while others are renewable, are being explored. However, there is substantial reason to believe that the greatest results can be achieved through improved standards in buildings.

According to the 2011 Buildings Energy Data Book (US DOE, 2011), buildings use approximately 40% of the nation's energy use. Approximately 56% of this energy is used for space heating and cooling as well as lighting applications, while 25% to 35% of this energy is wasted due to inefficient windows. All of these factors are directly impacted by the building envelope (Totten and Pazera, 2010). In addition to other functions (Kazmierczak, 2010; Sanders, 2006), successful building envelopes shield occupants from outside weather conditions while providing a connection to the outside.

Fenestration systems are a key element in achieving these goals. However, they are also the weakest link in terms of the thermal performance of the building envelope (Oldfield et al. 2009). This is primarily due to the higher U-value found in windows relative to wall systems. However, Johnson et al. (1984) found that well designed fenestration systems can reduce total building peak demand by up to 14-15%. Therefore, fenestration system selection is an essential part of reducing the buildings energy use profile.

There are currently a wide variety of different high efficiency window systems on the market (Straube, 2010); however, selecting the appropriate window systems is not a simple process. Specifying the best window system for a given space requires an understanding of exactly what the requirements for that space are and what window systems can provide.

The three main components that should be considered when specifying a window system are the whole window U-value, the Solar Heat Gain Coefficient (SHGC), and the Visual Transmittance ($T_{vis}$) of the glass. These values can be found in manufacturer literature as well as through NFRC (National Fenestration Rating Council) performance labels. The U-value measures the rate of heat flow (measured in Btu/(hr*ft$^2$*°F)), through a building component due to conduction, convection, and radiation. The Solar Heat Gain Coefficient (SHGC) measures the amount of incident solar heat gain transmitted through the system. This ratio varies from 0 (no solar gain transmitted) to 1 (solar gain completely transmitted). Visual Transmittance ($T_{vis}$) is a term used to describe the percentage of the visible portion of the solar spectrum that is transmitted through glazing. A $T_{vis}$ of 1 means that all of the visible light is transmitted through the window; whereas a $T_{vis}$ of 0 means that the window does not transmit any visible light.

The principal challenge of specifying fenestration systems comes from weighing the merits of each of these inter-related values. Improvements to the U-value and SHGC often come at a cost to the clarity of the window transparency. In some colder climates, it may seem advantageous to use a system with a low U-value and a high SHGC. In hotter climates, limiting the solar heat gain is a primary concern. For mixed climates, the decision making process ultimately comes down to balancing each property. However, the effects of each window system on the buildings annual energy performance are often difficult to judge. The main objective of this study was to investigate the performance of various types of glazing technology across multiple climates with the goal of determining how each system performs annually.

## PARAMETERS OF THE STUDY

This study compares the effect of using various glazing technology on the annual energy consumption of two model buildings in five different locations across the United States. The thermal and energy analysis was carried out using several different energy analysis software packages.

### Model Buildings

In order to determine the effect of fenestration systems on the energy performance of a variety of different buildings, this study considered two types of buildings: Residential and Small Commercial. Actual buildings were used to develop the parameters for each case. Data was gathered based on a combination of site visits and construction drawings. Any assumptions and simplifications made were maintained in all iterations.

For the residential scale building, a 1437 $ft^2$ model home in Boalsburg, PA was used. This single-story structure features a U-shaped plan and hip style roofs. Building 661 at the Naval Yard in Philadelphia, PA was selected as the small-scale commercial building. The 15,370 $ft^2$ building originally served as a recreation center and is now being converted into mixed office space.

## Glazing Technology

There are currently a broad range of different technologies that may be implemented into fenestration systems to improve energy performance. Some of these technologies rely on coatings to reduce the emittance of the glazing. Other products use “honeycombed”-like structures between glazing elements in order to improve the insulative performance. Still other products use less conductive materials such as polycarbonate in order to achieve better performance. For this analysis, a variety of different glazing options currently available on the market were used.

The products that were investigated fall into two basic categories, Transparent Systems and Translucent Systems. The transparent systems offer a high level of visual transparency, but typically result in wider heat swings and more potential glare under direct sunlight. In contrast, translucent systems do not offer views to the outside, but typically offer superior light diffusion as well as more stable thermal performance. Ultimately, the performance of products in each category is not directly comparable and the pros and cons of each must be weighed with the needs of the buildings use. A summary of the performance values used for each product is included in Table 1.

**Table 1: Glazing Product and Performance Properties Used.**

| Manufacturer | Glazing Product | U-Value (BTU/hr-ft2-°F) | Visual Transmittance | SC | SHGC | Glass Type |
|---|---|---|---|---|---|---|
| Advanced Glazing | Solera S | 0.20 | 0.55 | 0.60 | 0.52 | Translucent |
| Advanced Glazing | Solera L | 0.45 | 0.62 | 0.69 | 0.59 | Translucent |
| Bayer Material Science | Makrolon 5M/25-20 | 0.23 | 0.49 | 0.53 | 0.46 | Translucent |
| Duo-Gard | Triple Wall 25 + Nanogel | 0.18 | 0.40 | 0.56 | 0.48 | Translucent |
| Guardian Industries | Climaguard 71/38 | 0.29 | 0.71 | 0.45 | 0.39 | Transparent |
| Pilkington | SPACIA STII | 0.24 | 0.79 | 0.76 | 0.65 | Transparent |
| PPG | Solarban 70XL IGU | 0.28 | 0.64 | 0.31 | 0.27 | Transparent |
| PPG | Solarban 60 IGU | 0.29 | 0.70 | 0.44 | 0.38 | Transparent |
| PPG | Solarban 80 IGU | 0.29 | 0.48 | 0.28 | 0.24 | Transparent |
| PPG | Solarban R100 IGU | 0.29 | 0.42 | 0.27 | 0.23 | Transparent |
| PPG | Solarban z50 IGU | 0.29 | 0.51 | 0.36 | 0.31 | Transparent |
| PPG | Sungate 400 IGU | 0.32 | 0.76 | 0.69 | 0.59 | Transparent |
| PPG | Sungate 500 IGU | 0.35 | 0.74 | 0.71 | 0.61 | Transparent |
| PPG | Clear IGU | 0.47 | 0.79 | 0.81 | 0.70 | Transparent |
| Southwall | Southwall HM22/clear | 0.24 | 0.20 | 0.19 | 0.16 | Transparent |
| PPG | Clear Single Glazed | 0.99 | 0.89 | 0.94 | 0.82 | Transparent |

The products used are a sampling of those available from each manufacturer. For many products, entire studies could be undertaken on the coatings alone. In addition, since the performance values were taken from manufacturer literature, additional studies could be undertaken to confirm their accuracy. As such, this study is intended to provide a comparison of the performance of a sampling of product types. It is not intended to endorse or serve as a selection guide to specific products on the market.

### Location Parameters

The energy performance analyses were conducted in several different locations throughout the continental United States with the goal of representing varying climate types as is shown in Table 2.

**Table 2: Weather Type Corresponding to Each Location.**

| Location | Weather Type |
|---|---|
| Philadelphia, PA | Mixed, Humid |
| Miami, FL | Hot, Humid |
| Chicago, IL | Cold, Humid |
| Phoenix, AZ | Hot, Dry |
| Anchorage, AK | Cold, Dry |

### Software

The study was conducted using three different software packages. For the residential building model, Energy-10 and RESFEN were used. DesignBuilder was used as the commercial building software.

## RESIDENTIAL SCALE STUDY

### Energy 10 Analysis

Energy-10 is used during design primarily as a decision making tool for selecting and comparing the cost effectiveness of different energy efficient design solutions. The software architecture is modeled as a basic "shoebox" version of the design. While there are methods of augmenting this shoebox design to better resemble the real structure, these modifications do not necessarily provide more accurate results. Therefore, a highly simplified model with a rectangular shape (24'-0" x 77'-6") with a flat roof was used.

**Table 3: Percent Improvement of Each System in Comparison to Clear Monolithic Glass (Energy-10). The values highlighted in yellow indicate the most improvement while those highlighted in red indicate least improvement.**

| | Advanced Glazing Solera S | Advanced Glazing Solera L | BMS Makrolon | Duo-Guard | GIO Climaguard | Pilkington SPACIA | PPG Solarban 70XL | Solarban 60 | Solarban 80 | Solarban R100 | Solarban z50 | Sungate 400 | Sungate 500 | PPG Clear IGU | Southwall HM22Clear | PPG Clear Monolithic |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Philadelphia, PA | 18.38 | 11.61 | 16.31 | 18.30 | 13.05 | 18.85 | 10.82 | 12.81 | 9.86 | 9.55 | 11.38 | 15.67 | 15.04 | 12.49 | 9.55 | 0.00 |
| Chicago, IL | 18.28 | 11.29 | 16.27 | 18.28 | 13.05 | 18.98 | 11.16 | 12.86 | 10.28 | 10.09 | 11.60 | 15.45 | 14.82 | 12.42 | 10.34 | 0.00 |
| Anchorage, AK | 19.08 | 11.77 | 17.07 | 19.16 | 13.71 | 19.68 | 16.36 | 13.55 | 15.57 | 15.37 | 16.79 | 16.08 | 15.41 | 12.84 | 15.65 | 0.00 |
| Phoenix, AZ | 20.63 | 14.79 | 17.78 | 21.34 | 20.48 | 17.78 | 21.48 | 20.63 | 21.34 | 21.19 | 21.05 | 17.35 | 16.36 | 12.52 | 21.34 | 0.00 |
| Miami, FL | 14.37 | 11.65 | 9.32 | 15.53 | 19.81 | 9.32 | 24.66 | 20.19 | 25.63 | 25.83 | 22.72 | 11.65 | 10.87 | 7.18 | 26.80 | 0.00 |

The above results give a good indication of which technologies work best in which climates. The vacuum insulated glazing (Pilkington SPACIA) seemed to be most effective in climates where heating was a major concern. In these climates, insulation is of major importance. As can be seen in Table 1, the Advanced Glazing Solera S, Bayer Material Science Makrolon, and the Duo-Gard with Nanogel systems all provide a lower

U-value. However, the higher transparency of the VIG allows for the use of the sunlight for passive solar heating.

In the cooling dominated climates controlling the solar heat gain seems to be more important. In a hot and dry climate such as Phoenix, AZ, the spectrally selective coating used in all the Solarban product line proved to be more effective. These products also did well in the hot and humid climate of Miami, although the Southwall Heat Mirror product performed better.

As can be seen in Table 3, the range of improvement varied in each location, but was generally between about 10% and 20%. The climate with the widest range in performance was Miami, in which the clear IGU provided only 7.2% improvement while the HM 22 provided 26.8% improvement.

**RESFEN Analysis**

RESFEN is a simplified interface for using DOE-2, a widely used building energy analysis program. RESFEN simplifies the use of the DOE-2 engine to incorporate only those variables that apply to analyzing the effect of various fenestration products for residential buildings.

The percent improvement of each fenestration system over monolithic glass is shown in Table 4. In this study, the Solera S product was the most efficient fenestration system in Philadelphia, Chicago, and Anchorage. The Pilkington SPACIA system performed almost as well in each of the cold weather locations. In Miami and Phoenix, the Southwall Heat Mirror product had the best performance.

**Table 4: Percent Improvement of Each System in Comparison to Clear Monolithic Glass (RESFEN). The values highlighted in yellow indicate the most improvement while those highlighted in red indicate least improvement.**

| | Advanced Glazing Solera S | Advanced Glazing Solera L | BMS Makrolon | Duo-Guard | GIO Climaguard | Pilkington SPACIA | PPG Solarban 70XL | Solarban 60 | Solarban 80 | Solarban R100 | Solarban z50 | Sungate 400 | Sungate 500 | PPG Clear IGU | Southwall HM22Clear | PPG Clear Monolithic |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Philadelphia, PA | 38.00 | 25.27 | 35.24 | 37.79 | 29.72 | 36.94 | 23.35 | 25.05 | 22.72 | 22.51 | 23.99 | 26.54 | 25.48 | 19.53 | 24.84 | 0.00 |
| Chicago, IL | 37.99 | 25.38 | 35.26 | 37.82 | 29.64 | 36.63 | 23.34 | 25.04 | 22.66 | 22.49 | 23.85 | 26.75 | 25.72 | 19.42 | 24.87 | 0.00 |
| Anchorage, AK | 37.35 | 23.99 | 33.77 | 36.52 | 26.61 | 37.11 | 18.74 | 21.48 | 17.90 | 17.54 | 19.69 | 24.94 | 24.11 | 16.35 | 19.57 | 0.00 |
| Phoenix, AZ | 28.89 | 20.90 | 31.76 | 32.58 | 36.07 | 20.49 | 39.14 | 34.63 | 40.57 | 40.98 | 37.70 | 24.39 | 22.95 | 28.28 | 45.49 | 0.00 |
| Miami, FL | 16.99 | 13.29 | 21.79 | 21.57 | 29.85 | 7.41 | 37.47 | 30.50 | 39.65 | 40.52 | 35.08 | 16.99 | 15.47 | 25.05 | 45.75 | 0.00 |

As in the Energy-10 analysis, the product with the lowest U-value was the best performer in each of the climates where heating loads play a major role. This is because in cold weather climates, the ability to prevent heat loss will be of primary concern, leaving passive heating through solar heat gain secondary. In cooling climates, reducing solar heat gain was the primary factor as before. For example, the Pilkington VIG, which performed extremely well in each of the cold weather locations, performed very poorly in Miami and Phoenix. This is likely because the SHGC is still very high on this product, despite the presence of a low-e coating used in the system.

In some cases, nearly 50% improvement in energy performance was achieved by modifying the glazing system alone, which seems to stretch credibility. The magnitude of these values seems to be a telling statement about the primary function of RESFEN. RESFEN is used to help designer's select appropriate glazing systems for buildings rather than serve as a robust energy analysis tool. The principal problem in using RESFEN is that it makes it difficult for designers to determine the relative value in choosing a specific system over another that might suit other needs, such as cost or aesthetics.

## SMALL-SCALE COMMERCIAL ANALYSIS

### DesignBuilder Analysis

DesignBuilder is an energy modeling software developed using EnergyPlus as the analysis engine. This program allows the user to model a building with as much or as little detail as needed for the purpose of the simulation. For this analysis, the geometry was very detailed, while many of the other systems were highly simplified. For example, the HVAC design was simplified, meaning that DesignBuilder auto-sizes the HVAC systems according to algorithms taking into account typical occupancy, zone activity, and seasonal information.

The percent improvement over PPG monolithic uncoated glass is shown in Table 5. The values obtained from DesignBuilder were generally consistent with the previous analysis. As before, the products featuring a low U-value were the best performers in cold weather climates, while the products that reduce solar heat gain performed best in warm weather climates.

**Table 5: Percent Improvement of Each System in Comparison to Clear Monolithic Glass (DesignBuilder). The values highlighted in yellow indicate the most improvement while those highlighted in red indicate least improvement.**

| | Advanced Glazing Solera S | Advanced Glazing Solera L | BMS Makrolon | Duo-Guard | GIO Climaguard | Pilkington SPACIA | PPG Solarban 70XL | Solarban 60 | Solarban 80 | Solarban R100 | Solarban z50 | Sungate 400 | Sungate 500 | PPG Clear IGU | Southwall HM22Clear | PPG Clear Monolithic |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Philadelphia, PA | 9.71 | 5.88 | 8.55 | 9.72 | 6.81 | 10.23 | 5.97 | 6.71 | 5.57 | 5.47 | 6.03 | 8.19 | 7.85 | 6.71 | 5.69 | 0.00 |
| Chicago, IL | 12.29 | 7.88 | 11.16 | 12.37 | 9.39 | 11.79 | 8.76 | 9.31 | 8.38 | 8.29 | 8.74 | 10.43 | 10.00 | 8.48 | 8.69 | 0.00 |
| Anchorage, AK | 12.61 | 7.59 | 11.49 | 12.81 | 9.70 | 12.59 | 9.22 | 9.64 | 8.85 | 8.78 | 9.15 | 10.36 | 9.85 | 8.01 | 9.42 | 0.00 |
| Phoenix, AZ | 3.79 | 2.62 | 3.91 | 4.02 | 3.83 | 2.97 | 4.13 | 3.86 | 4.12 | 4.14 | 4.07 | 3.03 | 2.84 | 2.00 | 4.53 | 0.00 |
| Miami, FL | 2.47 | 1.96 | 3.25 | 3.01 | 3.78 | 1.13 | 4.51 | 3.86 | 4.63 | 4.72 | 4.38 | 1.86 | 1.68 | 0.85 | 5.27 | 0.00 |

The first observation that can be made is that the amount of improvement in annual energy use that can be achieved using various glazing systems is less for cooling dominated climates than for heating dominated climates. As is shown in Table 5, cooling dominated climates were only able to achieve in the range of ~0-5% improvement in energy use, whereas the heating dominated climates achieved up to ~13% improvement. The humidity is a likely explanation for why the analysis of the hot-humid climate showed less improvement than that provided by the hot-dry climate. In humid climates, the HVAC system has the requirement to manage a greater latent load than what is present in dryer climates. This means that these systems will work harder to manage the humidity regardless of the heat transfer through the building envelope. The only systems which performed better in the hot-humid climate were those with spectrally-selective coatings that limit solar heat gain (SHGC < 0.31).

In heating dominated climates, the best performers are those with the greatest insulative capacity. The spectrally selective systems that focus on passive solar heating (e.g. Sungate products) performed better than those that focus on preventing solar energy from entering the building (e.g. Solarban products). In cooling dominated climates, on the other hand, the highly insulative system only achieved moderate improvements, whereas those systems that prevent solar gain from entering the buildings achieved the best results.

## DISCUSSION

Although the performance trends were similar between residential and commercial buildings, the amount of energy savings was typically less for commercial buildings. Since a commercial building such as Building 661 has a much smaller exterior surface area to floor area ratio, it stands to reason that the choice of fenestration would have a lower effect on overall energy use. The results were then examined to determine if there was a correlation between product performance and product type. Each of the products was divided into category based on its function and performance values. These categories are listed in Table 6.

**Table 6: Glazing Category Definitions.**

| Category | U-Values | Visual Transmittance | Solar Heat Gain Coefficent |
|---|---|---|---|
| Translucent - Insulation | 0.18 - 0.2 | 0.4 - 0.55 | 0.46 - 0.52 |
| Transparent - Insulation | 0.24 | 0.79 | 0.65 |
| Spectrally Selective - SHG Reduction | 0.28-0.29 | 0.2-0.71 | 0.16-0.39 |
| Spectrally Selective - Passive Solar Gain | 0.32 - 0.35 | 0.74 - 0.76 | 0.39 - 0.61 |

The translucent – insulation based category included the Advanced Glazing's Solera S, the BMS Makrolon, and the Duo-Gard + Nanogel product. These products had low U-values ranging from 0.18-0.2, moderate visual transmittance values of 0.4-0.55, and moderate solar heat gain coefficients ranging from 0.46-0.52.

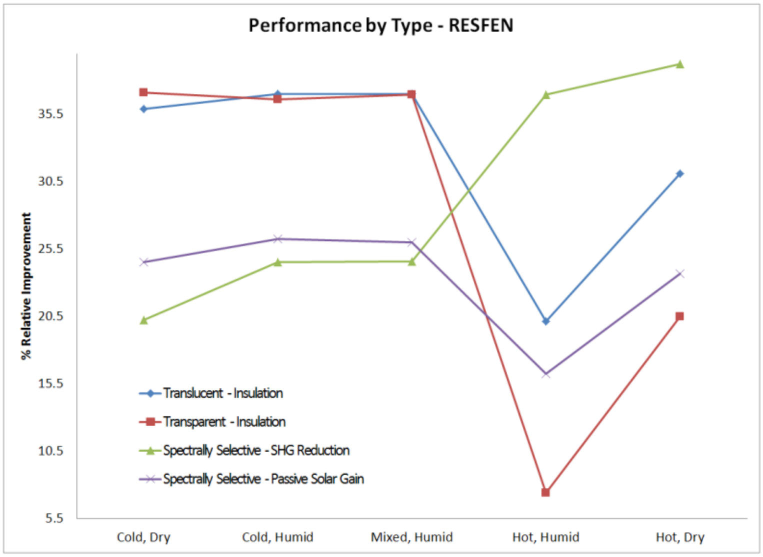
The transparent – insulation based category only included the Pilkington – SPACIA STII. This product features a U-value of 0.24, a high visual transmittance of 0.79, and a moderate-to-high solar heat gain coefficient of 0.65.

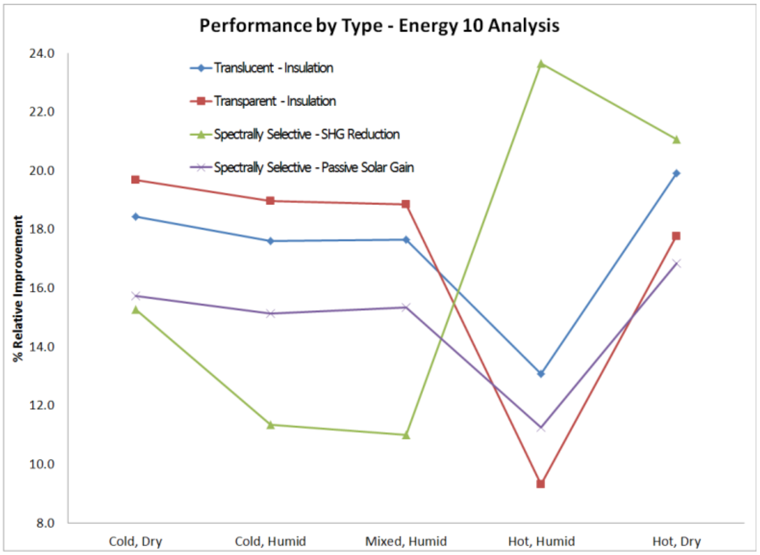
The spectrally selective – SHG reduction based category included the PPG Solarban products, the Southwall HM 22/Clear, and the Guardian Industries Climaguard. These values had U-values ranging from 0.28-0.29, visual transmittance values ranging from 0.2-0.71, and low solar heat gain coefficients ranging from 0.16-0.39.

The spectrally selective – passive solar heat gain based category included only the PPG Sungate products. These products had U-values ranging from 0.32-0.35, visual transmittance values ranging from 0.74 to 0.76, and solar heat gain coefficients ranging from 0.39-0.61.

Three products were excluded from all of these categories. The PPG Clear IGU and the PPG Clear Monolithic glass were excluded as they served primarily as baselines for the study. The Advanced Glazing's Solera L product was excluded as its most notable function is light diffusion (a daylighting characteristic not directly investigated) and does not fit easily into any of the above described categories.

For each climate type, the percent improvement was then averaged in each category. These values were then plotted, which can be seen in Figure 1. These charts can then be used by the designer as a decision making tool for which category of products best suits their needs. For example, a designer working on a project in a hot, humid climate can reference these charts to determine that a product that specializes in solar heat gain reduction would be best.



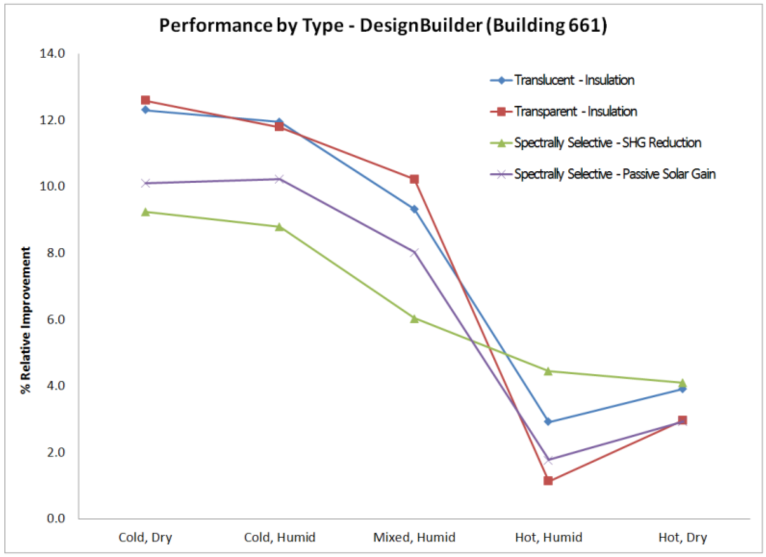



**Figure 1: Glazing System Performance by Type and Location for Commercial Buildings.**

Regardless of the application in which these charts would be used, it is important to note that these charts show relative improvement rather than absolute predictions of the energy savings one can achieve. The charts are based off data collected from the analysis of example buildings. While the trends of glazing performance are generally consistent between analyses, the absolute percent improvements can vary dramatically.

## SUMMARY AND CONCLUSIONS

This study involved the comparison of the performance of different glazing systems on annual energy use for residential and small scale commercial buildings in five different climates. The performances of 16 commercially available glazing products were investigated using three different software analysis packages.

While the results of each study varied slightly, there were several features that were common to each study. The highly insulated systems performed best in the cold weather climates, while spectrally selective systems that focus on reducing solar heat gain performed the best in warm weather climates.

The results for each product were then organized into different categories based on their manufacturer supplied performance values. Design curves were then created for each category that allows a designer to select an appropriate category of glazing system.

Based on the results of the study, the following concluding remarks can be made:

- Manufacturers define the performance of their glazing systems based on their U-value, $T_{vis}$, and SHGC. Owners and designers should consider the interaction of these three variables when selecting glazing products.
- In heating dominated climates, a low U-value should be prioritized. Products with spectrally selective coatings that allow for passive solar gain should also be used.

- In cooling dominated climates, a low SHGC should be prioritized. While low U-values are important, reductions in energy consumption will ultimately be determined by the glazing's ability to reduce solar heat gain.
- In mixed climates, a low U-value should be prioritized. In addition, it is important for designers to balance the spectrally selective coating to the heating/cooling requirements of the specific location.

## ACKNOWLEGMENT

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# TEMPORARY MASONRY STABILIZATION AND CONTAINMENT - HOW TO ADDRESS AN UNSAFE CONDITION ON A BUILDING FACADE

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## ABSTRACT

Typically unsafe conditions are discovered while completing the field work of a façade evaluation, unless a piece of material has already fallen to the ground. Safety has to be considered immediately, but professionals often require more assessment time and owners need time to obtain funding to begin the repair project. When an unsafe masonry façade condition is observed, design professionals and owners need to know the available options and how to react so the condition can be promptly addressed. There are several options available to address an unsafe condition, but choosing the correct option requires specialized expertise and field experience. Options will be discussed based on case studies of completed projects: including masonry removal or stabilization in place, containment netting installation, isolation of the safety concern by cordoning off the pedestrian area below, and installation of overhead protection to maintain pedestrian traffic flow. In most cases, the design professional has to discuss the options with the building owner in a way that allows the owner to make a decision that works for their specific requirements and building operations. Any delay in the process puts everyone at risk. This paper will discuss a logical approach to the options a building owner has when confronted with an unsafe condition, and the advantages and disadvantages.

## KEYWORDS

Stabilization, Containment Netting, Unsafe Condition, Overhead Protection, Pedestrian Safety

## INTRODUCTION

Building façade inspection requirements and standards are slowly becoming adopted by more and more cities. Owners are continuing to realize the necessity of reviewing their buildings to prevent façade deficiencies that could threaten the safety of pedestrians passing below (Fig.1). This has greatly increased the number of building inspections that are being completed, which is aiding the early detection of building façade deterioration and repair and restoration projects. With this assessment level comes an increase in the discovery of unsafe conditions, defined as "a condition identified at the time of inspection of a component or system that presents an imminent threat of harm, injury, damage, or loss to persons or property" in ASTM E 2270 Standard Practice for Periodic Inspection of Buildings for Unsafe Conditions. These conditions need to be addressed immediately to protect pedestrians and reduce owner's liability; however, the best course of action is not always clear. Understanding the key components of the various containment and stabilization options and how to best implement the approach is critical to the viability of the structure.

Fig. 1. Masonry chimney with severe displacement of the masonry has become an unsafe condition.

There are several factors that need to be considered when deciding the best steps to take to respond to an unsafe condition. The location of the building and the unsafe condition on the building, the usage of the building, façade construction, structural system, local codes, severity of the deterioration at the unsafe condition, surrounding exterior wall conditions, owners budget, schedule, etc. all need to be considered.

## OPTIONS

The first step in developing a course of action to address an unsafe condition is to review the available options. The options to address loose or unstable façade areas that could potentially dislodge and fall are outlined and then discussed hereafter:

1. Cordoning off pedestrian access
2. Installation of overhead protection
3. Removal of the loose or unstable façade elements
4. Installation of a temporary stabilization system
5. Installation of containment netting
6. Implementation of long-term repairs to address the deteriorated façade
7. Combination of the options

**1. Cordoning Off Pedestrian Access**

Cordoning off pedestrian areas (Table 1) is generally the most cost effective and easiest option to implement since it only requires some sturdy barriers and good signage. This option can usually be implemented the same day as the discovery. The area cordoned off should be conservatively sized and placed to encompass the potential danger zone; better safe than sorry. The issue comes with managing pedestrian flow around the cordoned off area (Fig.2). When the cordoned off area is at a heavily used walkway or entrance, signage must be installed that clearly directs the pedestrians along the desired alternate route. Even with good signage, the longer the area remains cordoned off, the greater the chance for pedestrian complaints, which can become a serious issue for an owner that leases space. If the barriers are in place for an extended amount of time, they must be maintained to ensure there are no breaches or areas that pedestrians can bypass.

Fig. 2. Area cordoned off because of falling stone pieces.

The real draw-back to long-term usage of this option is that it does not address the deterioration of the building façade. The loose or unstable façade areas will continue to deteriorate and could eventually come free from the building. This could drastically reduce the building façade's ability to resist moisture infiltration and may contribute to a significant increase in the rate of deterioration of the surrounding façade. As the façade continues to degrade, the cost to implement long-term repairs will rise exponentially.

| *TABLE 1: CORDONING OFF PEDESTRIAN TRAFFIC* | |
|---|---|
| ***ADVANTAGES*** | ***DISADVANTAGES*** |
| Easy to implement | Can impact pedestrian flow |
| Cost effective | Does not address façade deterioration |
| Allows for immediate response | Not a viable long-term solution |

## 2. Overhead Protection

Overhead protection installation (Table 2) is another option that is relatively cost effective and easy to implement. The design professional must work with the owner to confirm the overhead protection meets code requirements, but this is an option that typically can be completed within a week of the discovery, depending on the location of the building and the availability of firms in the areas that install and rent overhead protection. The benefit of this option is no disruption to the flow of pedestrian traffic (Fig. 3 & 4); however, overhead protection can be viewed as unsightly and could block ground floor signage on the building. Commercial space on the ground floor of the building can be significantly impacted by the installation of overhead protection.

Fig. 3. Overhead protection allowed for continued use of the front entrance.

Cost depends on the location and extent of the protection required, and consists of installation, dismantling, maintenance, and rental fees. If the overhead protection needs to remain in place long-term, this could become a costly expense. The owner can consider the option to purchase the materials, but would then be responsible for the maintenance of the equipment. The protection should include a top deck designed to resist impact loads, netting and a parapet to contain bouncing debris, deck membrane to limit dripping water, and lighting as necessary.

Fig. 4. Overhead protection installed along entire length of sidewalk.

| *TABLE 2: OVERHEAD PROTECTION* | |
| --- | --- |
| ***ADVANTAGES*** | ***DISADVANTAGES*** |
| Easy to implement | Can impact pedestrian flow |
| Cost effective for short term | Higher long-term cost |
| Can remain in place for extended periods | Does not address façade deterioration |

**3. Removal of the Loose or Unstable Façade Elements**

Removing loose material (Table 3) may be the fastest and most effective way to address the unsafe condition, depending on the accessibility of the loose or unstable façade elements. Many times, insipient spalls and loose façade fragments can be removed by hand or with small hand tools (Fig. 5). If the area of the unsafe condition has been accessed as part of the investigation, the investigative team may have the opportunity to remove some of the materials as a courtesy to the owner. When removing a loose or unstable piece, the weight of the piece must be carefully considered to make sure it is feasible to transport the piece to the ground. The stability of the surrounding façade elements must be closely reviewed to ensure removal of the loose or unstable piece will not cause additional façade elements to become loose or unstable. If the removal of the element creates an opening for excessive water infiltration, then temporary waterproofing should be installed.

Fig. 5. A large limestone spall was removed by hand from the façade.

Fig. 6. Loose pieces can be removed whenever feasible as long as doing so will not contribute to additional deterioration of the façade.

This is an option that should almost always be completed immediately when there are small loose façade elements that can be removed without causing additional damage (Fig. 6). If not immediately feasible, the owner can arrange for removal shortly thereafter the assessment. This option becomes more difficult when there are multiple elements on the façade and the reviewer cannot verify that all potential loose items have been removed. A comprehensive fragment removal program may be required to ensure all areas are addressed.

| *TABLE 3: REMOVAL OF THE LOOSE OR UNSTABLE FAÇADE ELEMENT* | |
|---|---|
| *ADVANTAGES* | *DISADVANTAGES* |
| Relatively easy to complete | Need sufficient access |
| Cost effective | Can contribute to façade deterioration |
| Does not affect the usage of the building | Not always feasible |

## 4. Installation of a Stabilization System

Stabilization system installation (Table 4) can be implemented using products specifically available for remedial anchoring or custom solutions. They can be implemented as long-term solutions that are part of a restoration project or as temporary support to provide immediate response to an unsafe condition. Whenever stabilization is used, both an engineer and a manufacturer's representative should be involved to confirm the product will be able to resist the forces necessary to keep the loose or unstable façade area in place. Installation must follow the manufacturer's recommendations and should be completed by a qualified contractor who has familiarity with the selected product.

Fig. 7. Stainless steel anchors and plates support the masonry that was displacing away from the wall.

Stabilization can provide a solution that can remain in place for several years (Fig. 7), although it usually comes with a higher initial cost and extended schedule. Stabilization requires time for an engineering review of the construction, design, and product selection. In addition, the stabilization anchors require access and time for the contractor to properly install. Access to the area may require significant effort and associated cost, depending on the building. There are many situations where stabilization is not feasible; the loose piece is too heavy to support, the structure/back-up are also unstable, or the façade is too severely deteriorated. When stabilization is feasible, it can provide a good option that does not disrupt the usage of the building and does not greatly affect the aesthetics of the building.

| *TABLE 4: INSTALLATION OF A STABILIZATION SYSTEM* | |
|---|---|
| ***ADVANTAGES*** | ***DISADVANTAGES*** |
| Will perform for years | Need sufficient access |
| Does not affect the usage of the building | Design and installation take time |
| | Not always feasible |

## 5. Containment Netting

Containment netting (Table 5) is used to prevent any loose pieces of the façade from falling to the ground. Netting comes in a wide range of meshes. The size of the mesh should be selected based on the anticipated size of the pieces that may come loose from the building. Many times, netting with a smaller mesh used to contain minor debris can be combined with a wider, stronger mesh that can support larger sections of the façade (Fig. 8). All netting should be manufactured by a reputable company that specializes in ultraviolet stabilized debris and containment netting and installation accessories. Accessories must be made from non-corrosive materials to prevent failure of any anchorage or staining on the façade. Containment netting must be installed by a qualified contractor and should never be done without skilled craftsmen and quality materials (Fig. 9).

Fig. 8. Properly installed netting at the top of a church tower.

Fig. 9. Poorly installed netting done by personnel without the appropriate expertise.

The benefit of containment netting is the flexibility it provides; containment netting can be installed at many building locations (Fig. 10). The netting can be obtained and installed in a relatively short time frame. Netting is not a permanent solution; it is intended to be temporary, which is typically two to three years. The netting weakens when exposed to sun and the elements and through mechanical abrasion from wind. Keeping the netting in place too long can put the owner at risk, and does nothing to address the deterioration of the façade.

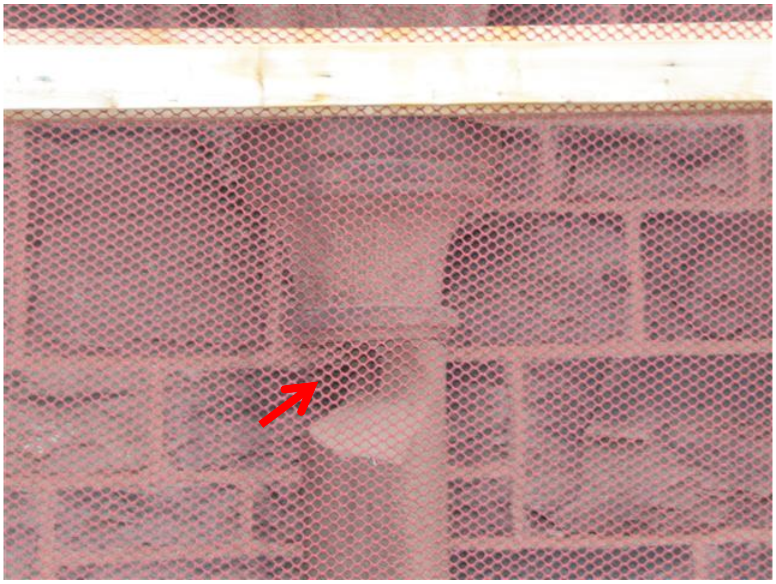

Fig. 10. Containment netting installed at a column where large pieces have spalled and fallen from the building.

| *TABLE 5: CONTAINMENT NETTING* | |
|---|---|
| *ADVANTAGES* | *DISADVANTAGES* |
| Flexibility allows use in most locations | Limited life span |
| Relatively easy to implement | Does not address façade deterioration |
| Does not affect the usage of the building | Higher cost |

## 6. Long-Term Repairs

Completing long-term repairs (Table 6) that address the building façade deterioration will address the unsafe condition and help limit other areas from developing into unsafe conditions, and is ultimately the most effective long-term remedy. The presence of an unsafe condition is a clear indication of severe degradation of the façade. While the unsafe condition typically occurs at the worst area of the wall, other areas are usually in an advanced state of decline.

To complete the restoration of a façade with significant deterioration takes planning, coordination and a longer schedule. The cost to complete the restoration will typically be substantially higher than any of the other short-term options (Fig. 11). Due to the level of façade deterioration once unsafe conditions are identified, the restoration work cannot be overly deferred. With the desire for long-term performance and an adequate budget, it makes sense to complete the repairs immediately to address façade issues, instead of spending money on temporary options and allowing deterioration to accelerate.

Fig. 11. Restoration of the facade provides the owner with a long-term result.

| TABLE 6: LONG-TERM REPAIRS | |
|---|---|
| ADVANTAGES | DISADVANTAGES |
| Provides long-term effectiveness | High costs |
| | Significant time to implement |
| | Will affect usage of building |

**7. Combination of Options**

Combining options provides an additional resource to tailor the unsafe condition correction to the client and building. The installation of barriers or overhead protection can be used in the short term to buy time and allow the owner and design professional to select a stabilization system or design a restoration project (Fig. 12). Some options cannot be implemented immediately, so it is typical for the installation of barricades to be the first step; however, since this can cause a major disruption to the usage of the building, another option is often implemented as soon as possible. The building typically needs some level of restoration repairs; with the critical owner decision of when to implement the repair program. The use of multiple options can help the owner address the unsafe condition with minimal impact to the building operations in a progression of logical steps.

Fig. 12. Overhead protection allows continued use of the entrance while long-term restoration repairs are being completed.

## CONCLUSSION

Inspecting a façade with guidance from ASTM E 2841 "Standard Guide for Conducting Inspections of Building Facades for Unsafe Conditions," is a critical first step in identifying potential issues. When dealing with an unsafe condition, every building has unique conditions and constraints. The owner and design professional need to work closely to develop a plan specific to the current situation and with consideration to the future needs of the building. Each option should be reviewed and compared so the best course of action can be selected, which is largely determined by client requirements. Dealing with an unsafe condition can be difficult, but the most important consideration and owner responsibility is to protect public safety. It is critical to remember that these stabilization and containment options are largely intended to be temporary in nature, and a full façade assessment should be used to determine the appropriate long-term repair solution. The root cause of the failure needs to be sought out and corrected, not just the effects manifesting as unstable façade areas. Addressing an unsafe condition on a building façade can be logically diagnosed and addressed by reviewing the advantages and disadvantages of the various options and their applicability to the subject building.

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# Building envelope leakage measurement using the air-handler fan pressurization approach

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## Abstract
This research is a case study performing the air-handler fan pressurization test in a real building. The test has been performed following an existing test method (i.e. CGSB-149.15-96). The test building is a 5-story office with a square (32.4m x 32.4m) footprint built in 2001 at Daejeon, South Korea. The gross area of the building is 6,165m$^2$ and the curtain wall structure is used as the building envelope. Atrium is located at the center of the building form 1$^{st}$ floor to 5$^{th}$ floor, and offices are placed around the atrium in each floor. The test building has four air-handling units, but the unit located at the basement was out of order. Consequently, the 3 air-handling units installed at the 1$^{st}$ floor and the 5$^{th}$ floor were used to pressurize the building. To measure the whole building envelope air leakage, the SA airflow rates in each air handler, operated at the 100% outdoor air mode with closed return and exhaust air dampers, were monitored together with the building pressure. Five differential pressure gauges were installed to figure out the mean differential pressure between inside and outside of the building. This paper provides some practical information acquired in the field measurement of envelope leakage using the established air-handler fan pressurization test method.

Keywords : AHU pressurization test, Air-tightness, Air leakage test ,Building Envelope, Fan pressurization test

## 1. Introduction

The building envelope leakage has significant impact on building energy consumption, mold, and moisture problems in buildings. According to CIBSE (1996), since infiltration is uncontrolled and inevitable, it is recommended that the HVAC system should have additional capacity than required. However, the building with relative good air-tightness is the first step for realizing low energy consumption in building operation.

As for the air leakage measurement, the tracer gas method and fan pressurization (or depressurization) test approach are commonly used. In the tracer gas method, $SF_6$ or $CO_2$ gas is released inside the test zone. And then, the concentration decay or the amount of gas released is monitored for determining the leakage rate through the envelope of the test zone. However, the tracer gas test is relatively expensive and should be done by well-trained person.

The fan pressurization test using the blower door is more widely used in the leakage measurement than the tracer gas approach, but mostly for small-scale buildings. On the other hand, CGSB Standard-149.15 suggested the fan pressurization test using the HVAC system installed in a test building, which can be applicable to large or tall building leakage tests, while the actual measurement results and case studies found from open literature are very rare.

Consequently, this research introduces the envelope leakage measurement results for a 5-story office building and the practical information acquired from the actual air-handler fan pressurization test.

## 2. Literature review

Pressurization test using air-handling unit was suggested by Shaw et al. (1973). They verified the applicability of the air-handler fan pressurization approach for large buildings. Tamura and Shaw (1976) measured the air leakage using air-handling units at eight buildings in Canada. Bahnfleth et al. (1999) and Jeong et al. (2009) also verified the applicability of the air-handler fan pressurization test method via field measurements.

As for the test standards, ASTM (2003) indicates required equipment and test conditions, in addition to the detailed test procedure for the fan pressurization test. ISO (2006), CIBSE (1996), and CGSB (1996) standards suggests the leakage measurement using a large and multiple fans, or existing air-handlers for large-scale buildings. In general, the leakage measurement result is expressed by power-law equation indicating the relationship between the indoor-to-outdoor pressure difference and the leakage flow rate Eq. (1).

$$Q=C(\triangle P)^{n} \tag{1}$$

where; Q : Air leakage in building, $m^3/h$
$\triangle P$: Pressure difference between inside and outside, Pa
C : flow coefficient, $m^3/(s{\cdot}Pa^n)$
n : flow exponent, dimensionless

On the other hand, there are several established indicators commonly used for rating the air tightness of a building (Table 1). However, the target pressure difference (i.e. 50 or 75Pa) required in some indicators may not be reached by the air-handler fan pressurization approach. In this case, the power-law function acquired from the test is used for predicting the leakage under the given target pressure.

## 3. Air-handler fan pressurization test

### 3.1. Test building overview

The test building (Fig. 1) is a 5-story office building located in Daejeon, Korea. It is a steel-structured building with 6,165 $m^2$ total floor area, served by four air handlers. One air handler (i.e. AHU-4) is installed in the mechanical room on the basement floor, serving the first and the second floors. The air handler in the first floor mechanical room (i.e. AHU-1) serves the atrium. Two air handlers (i.e. AHU-2 and AHU-3) are located in the mechanical room on the fifth floor and serve the rest of the building. The proposed fan pressurization test was performed for two consecutive days.

The window-to-wall ratio for each facade of the building is as follows; South facade: 38%; East facade: 21%; West facade: 21%; North facade: 12%.

Table 1 Air Tightness Indicator

| Indicator | Equation | Related Standard |
|---|---|---|
| $Q_{50}$, air leakage rate, $m^3h^{-1}$ | $Q_{50} = C \cdot L_{50}$ | - |
| ACH50 (Air Change Rate) | $ACH50 = \frac{CFM50 \times 60}{\text{Building Volume}(ft^3)}$ | DIN EN 13829 |
| CFM75/$ft^2$ | CFM75/$ft^2$ = CFM75 / Floor area in $ft^2$ | USAGE, GSA |
| ELA (Effective leakage Area) | $ELA = \sqrt{\frac{\rho}{2}} \kappa P_r^{(n-0.5)}$ at 4Pa | ASTM E779-03 |
| EqLA (Equivalent Leakage Area) | $EqLA = \sqrt{\frac{\rho}{2}} \kappa P_r^{(n-0.5)}$ at 10Pa | CAN/CGSB 149.10 |
| NL (Normalized leakage area) | $NL = 1000 \frac{ELA}{A_f} (\frac{H}{2.5})^{0.3}$ | ASHRAE Standard 119 |

Fig. 1. Test Building

**3.2 Test overview**

The test was performed on April 21, 2012 using existing air-handler fans. Outdoor air temperature and wind speed were 12.52±0.23°C and 1.26±0.72m/s, respectively, which satisfies the existing measurement standards. All interior doors with no security problem were opened during the test. The elevator shaft vent and restroom vents were all sealed on the rooftop.

The elevator shaft vent and the toilet vent on the roof were sealed using duct tapes and plastic sheeting. A portable weather station was located near the test building, and measured the outdoor temperature, wind speed, and atmospheric pressure. The indoor air temperature was also monitored.

The outdoor pressure tap should be located at each side of the building and averaged using a tube manifold. However, it was impossible at the site, so the pressure tap was located at the middle of the south-facing exterior wall of each floor. The indoor pressure tap was also located on each floor.

Five pressure gages were used for measuring the differential pressure of each floor. All the pressure gages was located on the 3rd floor, and tubes from outdoor and indoor pressure taps were connected to each gage. The detailed tube length used in this test is shown in Table 2. The nominal tube diameter is 0.004m. According to CGSB 149.15, the tube length is unrestricted, when more than 1mm of tube diameter is used.

Table 2 The details of tube length

| Floor | Indoor tube length | Outdoor tube length | Floor height |
|---|---|---|---|
| 1st floor | 29.5m | 33.4m | 4.5m |
| 2nd floor | 25m | 28.9m | 3.9m |
| 3rd floor | 21.1m | 25m | 3.9m |
| 4th floor | 17.2m | 21.1m | 3.9m |
| 5th floor | 21.1m | 25m | 3.9m |

Before the test is started, return air dampers and exhaust air dampers were completely closed except the outdoor air dampers (Table 3), and the exhaust air outlets located on the roof and ground floor were sealed with plastic sheeting (Fig. 2). Unfortunately, AHU-4 was out of order, so the test was performed only with the remaining three air handlers.

Fig. 2**. Sealed** exhaust air outlets

All air-handling units of the test building were VAV types, and the air flow rates of each air-handlers was adjusted by modulating the fan speed. During the test, all VAV boxes installed were set to fully-open position, and the outdoor air flows were measured by existing supply air flow sensors. The background pressure of the test building was measured before and after the test.

Table 3 Air-handler damper position and status

| Damper | AHU-1 | AHU-2 | AHU-3 |
|---|---|---|---|
| EA damper | Closed | Closed | Closed |
| RA damper | Closed | Closed | Closed |
| OA damper | Open | Open | Open |

## 4. Measurement Results

### 4.1 Air-handler fan pressurization

Table 4 shows the results. The outdoor air flow rates at each air hander were measured for each of the five different building pressures (i.e. Test-1 through Test-5).

The maximum pressure difference realized in the test was 11.37 Pa. Although this pressure difference was much lower than the conventional target value, the fan pressurization test was performed by decreasing the building pressure gradually from the maximum pressure acquired in Test-1. The base pressure measured before and after the test was -1.2 Pa. Air flow rates of the air-handlers were corrected for the outdoor and indoor temperature difference based on ASTM standards.

Table 4 Air-handler fan pressurization test results

| Test No. | Building Pressure (Pa) | OA flow rate ($m^3/s$) | | | Envelope Leakage ($m^3/s$) |
|---|---|---|---|---|---|
| | | AHU-1 | AHU-2 | AHU-3 | |
| Test-1 | 11.37 | 8.10 | 6.80 | 0.83 | 14.46 |
| Test-2 | 10.11 | 7.19 | 6.05 | 0.83 | 12.75 |
| Test-3 | 7.70 | 6.28 | 5.30 | 0.83 | 11.04 |
| Test-4 | 4.58 | 5.36 | 4.55 | 0.83 | 9.34 |
| Test-5 | 4.62 | 4.45 | 3.80 | 0.83 | 7.63 |

Fig. 3 shows the log-log plot of the test results. The resulting power-law equation is expressed as Eq. (2). The $R^2$ value of the power-law equation is 0.91.

$$Q = 3.557\ (\Delta P)^{0.563} \quad (2)$$

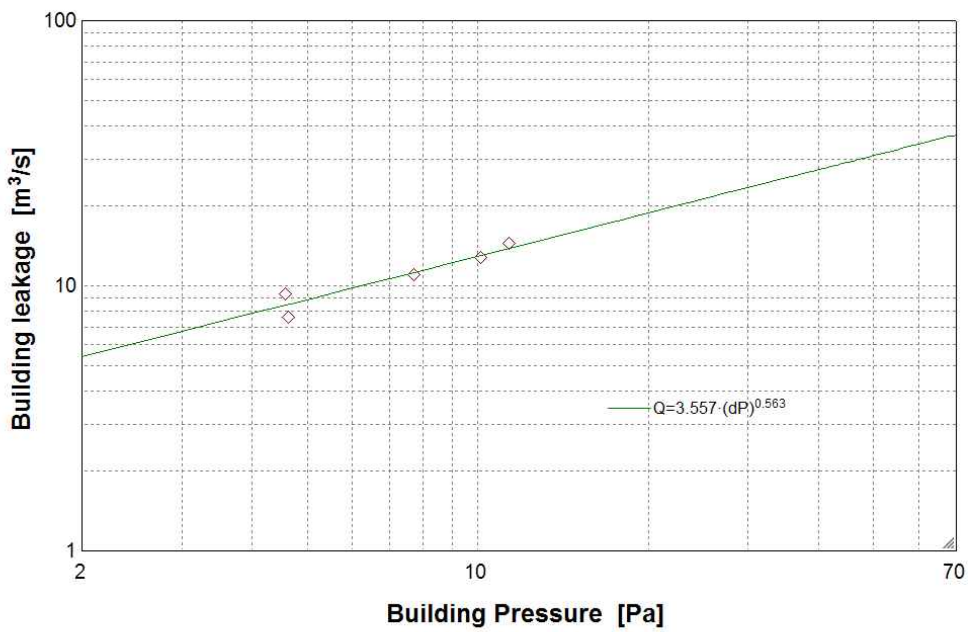


Fig. 3. Pressurization test using the air-handler fan

Based on the envelope air leakage characteristic obtained from the measurement, the level of air-tightness of the test building was rated by the established indicators shown in Table 1.

The ACH50 of the test building was 6.1 air-changes per hour, but it is almost 2-3 times higher than the recommended value of DIN EN 13829 (i.e. 1.8~3.6 air-changes per hour). The ELA and the EqLA of the test building estimated by ASTM E779 and CAN/CGSB

149.10 were 3.5cm$^2$/m$^2$ and 2.6cm$^2$/m$^2$, respectively. However, they are also about 4 times higher than the upper limit indicated by the LEED rating (0.87 cm$^2$/m$^2$) and Canadian R-2000 (0.69 cm$^2$/m$^2$) standards. Consequently, one may conclude that the test building is not a building with the good air-tightness performance.

In this research, the air-handlers could not pressurize the test building up to the target pressure (e.g. 50Pa) commonly used in the conventional fan pressurization test approach. It may increase uncertainty of the estimated leakage rate for the high pressure difference condition (e.g. ACH50).

**4.2 Cost information**

In order to provide basic information for estimating the cost of the air-handler fan pressurization test, the man-hours (MH) and equipment costs per unit floor area are summarized.

As for the labor cost, the test was performed by 10 technicians. They worked for eight hours including planning, sealing, main tests, and the final clean-up. It means that the air-handler fan pressurization test perfomed in this building spent 80MH. By normalizing it for the floor area, one may conclude that the test needs the labor input of 0.018MH per unit floor area (i.e. 0.018MH/m$^2$). The total labor cost spent for the test was $3,854(USD). In Table 5, the detailed information of the total cost including equipment, materials, and labor spent for the test is summarized. The total cost was $12,500(USD), it means that the air-handler fan pressurization test may require about $2 per unit floor area.

Table 5 Total costs spent for the test

| Cost factors | | Description | Unit cost($) | Quantity | Cost($) |
|---|---|---|---|---|---|
| Equipment and material expenses | Differential pressure gauge | Testo521-6 | 1,383.25 | 5 | 6,916.25 |
| | thermometer | Testo625 | 533.30 | 1 | 533.30 |
| | Weather station | DAVIS Vintage Pro 2 6152 | 829.95 | 1 | 829.95 |
| | Manifold and tube | | 276.65 | - | 276.65 |
| | Other sealing material | | 92.21 | - | 92.21 |
| Labor cost | | | 3,854.4 | 10 | 3,854.4 |
| | | | Total cost($) | | 12,502.76 |

## 5. Conclusion

In this research, it was found that the air-handler fan pressurization approach may not generate an adequate indoor-to-outdoor pressure difference recommended by existing test standards, because of the insufficient capacity of air handler fans and/or unfavorable site conditions. The power-law equation derived from the air-handler fan pressurization test may be used for estimating or rating the envelope leakage level not only for low pressure (i.e. 4 Pa) but also for high pressure (i.e. 50 Pa), however, one may need a means to realize higher target pressure in order for minimizing negative impact on the test from the harsh outdoor conditions. It may critical especially for high-rise or tall building leakage tests. As for the cost required for the use of air-handler fan pressurization approach, it was found that about $2/m$^2$ could be spent.

## Acknowledgement

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# FACTORS CONTRIBUTING TO GLOBAL DIFFERENCES IN BUILDING ENCLOSURES

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## ABSTRACT

A study has been undertaken to compare local considerations for the design and construction of building enclosures in different global markets. This ongoing study explores significant differences in building enclosures on mainstream, modern, low-to-mid-rise commercial buildings in four major global construction markets: Europe, Far East, Middle East, and North America. Experts with international experience were interviewed on what they perceived as differences in the various global markets and also completed a survey to develop a comprehensive list of weighted factors underlying observed global differences in building enclosures.

Prominent factors that contribute to global differences in local considerations for the design and construction of building enclosures are presented to inform building enclosure professionals on local considerations when conducting building enclosure activities internationally. The four factors most commonly mentioned through the interviews were energy codes, climate, local capabilities, and energy. Included in this paper is how each factor was perceived to play a role in creating global differences in building enclosures.

**Keywords:** Building enclosure, globalization, international construction, local knowledge

## INTRODUCTION

The need for more infrastructure and buildings in the various global markets creates an opportunity for Architecture, Engineering, and Construction (AEC) firms to expand their international scopes. Although companies in the AEC industry are beginning to practice internationally, global variations exist and account for differences seen in construction techniques and processes used on construction projects across the world (Yates 2007). When working on projects internationally, it is inappropriate for an AEC firm to design and construct projects to domestic standards. Global markets possess their own unique characteristics that could have major implications for a project's ultimate success.

Analyzing the various parts that come together to form a building, the authors postulate that the part of the overall building most influenced by local characteristics is likely the building enclosure. The *building enclosure*, known interchangeably as the *building envelope*, is defined as the part the building that separates the interior environment from the exterior environment to which it is exposed (Straube and Burnett 2005). It serves two overarching functions: (1) to enclose and make sense of the internal volume it contains; and (2) to delineate and characterize the external space (Lovell 2010). In order to function as an interface for the internal space from the exterior environment, many components work together within the enclosure to achieve satisfactory conditions for building occupants. With these various interactions, the design and construction of the building enclosure is an integrated process involving many parties, including architects, engineers, manufacturers and contractors. The collaboration of these parties makes design and construction of the building enclosure a highly interdisciplinary endeavor.

It is important that building enclosure professionals in AEC firms undertaking international projects understand local considerations. Limited sources of open literature (Ledbetter et al. 1992, Santos 2007, and Bilow 2012) address the building enclosure in the context of global markets. Firms wishing to learn about local conditions in a new international market must conduct their own independent research, which requires significant time and effort. There currently exists a need to create more open literature to inform AEC firms working on building enclosures internationally on differences that could exist in different global markets. Such information could reduce the chance of learning international nuances "the hard way."

This research seeks to identity factors that account for global differences in building enclosures as perceived by professionals who have familiarity with multiple international markets. Upcoming research initiatives will includes fully articulating the differences that exist in building enclosures in different global markets. The authors also plan to develop case studies on building enclosure projects in the four selected global markets to illustrate the more salient research findings.

## BACKGROUND

The potential to work on international projects allows AEC firms to remain competitive in the building industry while simultaneously creating opportunities in new markets. Recent advances in telecommunications technology have opened new markets worldwide within the building construction industry not seen in previous times (Ngowi et al. 2005). Firms are now able to work on foreign projects without ever leaving their homes through the Internet (Yates 2007). This phenomenon is a manifestation of globalization, which Ngowi et al. defines as "a situation where political borders become increasingly more irrelevant, economic interdependencies are heightened, and national differences are accentuated due to dissimilarities in societal cultures and central issues of business." The advent of globalization within the AEC industry has brought foreign methods of design and construction to new markets. Firms that are embarking on new international ventures are bringing along their familiar ways of practice. However, these domestic practices may not be appropriate for the international market in which they are utilized.

Although working on international projects has the potential for significant payoffs, there are significant risks for AEC firms that would not be found in domestic projects. Yates (2007) defines such risks as coming in the form of potential outcomes of uncertainties that are unfavorable to a given condition or situation. A major contributing factor for increased risks is related to the lack of familiarity with a new project location. Firms who are unfamiliar with their new markets are labeled as suffering from "liability of foreignness" (Zaheer 1995). This situation makes firms entering new markets susceptible to risks that otherwise would not be present if they had appropriate experience.

Acquisition of local knowledge is imperative for AEC firms when entering new countries (Lord and Ranft 2000). Javernick-Will and Scott (2010) conducted a study focused on identifying differences in rules and political systems, differences in norms and customs, and differences in values and beliefs on international projects, which they referred to as "institutional knowledge." The study concerned itself with building upon the theory that obtaining a project's local knowledge would result in a reduction of knowledge gaps, the difference between institutional knowledge that is needed on an international project and the knowledge the firm actually possesses (Peterson et al. 2008). Acquisition of such institutional knowledge decreases the risks an AEC firm faces when working internationally.

## RESEARCH METHODOLOGY

The means of research in this study consists predominantly of interviews with professionals who possess knowledge of building enclosures in multiple global markets. The interview method is flexible and remains a popular choice for research studies related to the built environment (Knight and Ruddock 2008). The interview process utilizes a semi-structured interview. Each question includes a brief introduction of the topic to be discussed, followed by the interviewee providing a response based upon his/her experiences. Follow up questions are asked by the interviewer to further probe or clarify respondent comments.

To encapsulate the interdisciplinary nature of the building enclosure, interviewees with various backgrounds were sought, including researchers, manufacturers and consultants. Table 1 provides a breakdown of the interviewees' backgrounds to date. It was essential to select a diverse pool of research participants in order to capture views from the diverse parties responsible for creating a building enclosure. The three categories comprising the interviewees' backgrounds cover a wide base of knowledge in various aspects of the building enclosure.

**Table 1: Research Participant Backgrounds as of September 2012**

| | Researchers | Manufacturers | Consultants* |
|---|---|---|---|
| No. of Participants | 3 | 6 | 9 |

*Consultants are defined as professionals contracted to work with engineers, architects, and contractors on various aspects of the building enclosure

In addition to various professional backgrounds of the research participants, efforts were made to ensure that each major global market was covered. Table 2 displays the global markets for which each interviewee expressed a familiarity of local considerations.

**Table 2: Research Participants Global Market Knowledge as of September 2012**

| Participant | Europe | Far East | Middle East | North America |
|---|---|---|---|---|
| 1 | x | | | |
| 2 | x | x | x | x |
| 3 | x | | | x |
| 4 | | x | | x |
| 5 | x | | x | x |
| 6 | x | | | x |
| 7 | x | x | x | x |
| 8 | x | x | | x |
| 9 | x | x | | x |
| 10 | x | | | x |
| 11 | x | x | | x |
| 12 | x | x | x | x |
| 13 | | | | x |
| 14 | x | | | x |
| 15 | x | | | x |
| 16 | x | x | x | |
| 17 | x | | | |
| 18 | x | x | x | x |
| Total | 16 | 9 | 6 | 15 |

Research participants were interviewed through either telephone or email communications. In total, sixteen participants were interviewed through phone, while the remaining two communicated through email. Each phone interview, with permission from the participant, was recorded with an electronic recording device. In addition to notes taken during the interview process, each recording was transcribed. A coding process was utilized to analyze the major topics covered in the interview process. Codes were created for each topic introduced by the interviewee. A sample of codes used in this research is provided in Table 3. Each documented piece of information corresponding to a code was organized so that the contents could be analyzed for similarity and differences in responses.

**Table 3: Sample of Codes Used to Analyze Interviews**

| Interview Code | Description |
|---|---|
| Building Codes and Standards | Use of local model building codes in the design of building enclosures. Apply this interview code when discussion of applicable laws/mandares arises. |
| Design Responsibility | Principal party with final authority of the building enclosure design/construction. Apply this interview code when discussion of parties responsible for the design/construction of building enclosure arises. |
| Climate | The expected weather in a given environment over a long period of time. Apply this interview code when discussion of weather conditions in a global region arises. |

## GLOBAL MARKET CONDSIDERATIONS FOR THE ENCLOSURE

The following section describes the four most common mentioned perceived factors as to why building enclosures differ in various global markets as stated by interviewees. The list is by no means exhaustive and presents only early findings of the research; however, it provides some insights as to why global differences in building enclosures exist. It is anticipated that these identified factors will help inform building enclosure professionals as to relevant considerations when working in new global markets.

### Building Energy Codes

The first perceived factor mentioned for differences in building enclosures across global markets was building energy codes, which prescribe minimum energy performance ratings that a given building must achieve in service. Many interviewees noted that differences in energy codes greatly affected the design and construction of building enclosures in different markets.

A common example mentioned by interviewees was the difference in mandates of the minimum thermal conductance of wall constructions between North America and Europe. It was perceived by the interviewees that mandates in Europe were significantly stricter than those in North American codes. One interviewee conveyed a story of a Canadian contractor working on a British project questioning whether a wall design specified was physically possible in order to achieve the energy performance requirements of a European code. The interviewee noted that the skepticism of the contractor was likely due to his unfamiliarity with the stringencies of European standards and pointed to existing European projects to demonstrate that the design was achievable.

Generally speaking, energy codes in the Far East and Middle East were found to be less stringent in comparison to those found in Europe and North America. Several interviewees mentioned that in the absence of local energy codes in these global markets, they referred to

North American or European codes and standards. It was noted that some developing countries in the Far East and Middle East were beginning to become more aware of the importance of mandating minimum energy requirements and that future codes and standards released in these regions would reflect such a trend.

**Local Climate**

Local climate was the most prominent non-manmade factor accounting for global differences as reported by the interviewees. Climate, according to the Merriam-Webster dictionary, is "the prevailing influence or environmental conditions characterizing a group or period." Wind characteristics and solar exposure, although aspects of local climate, were coded separately from the "climate" category due to the depth of discussion related to wind and solar exposure brought up during the interview process. Here, climate refers to temperature, precipitation, and relative humidity at a given site.

All interviewees agreed that local climate played a factor in creating a difference in building enclosure for varying markets. However, one interviewee noted that it was difficult to qualify climate-related differences in the building enclosure in the context of global markets. This interviewee stated that the building enclosure would differ by climate, not specifically based upon global market. A cold climate North American building enclosure would be treated much the same as a European cold climate building enclosure, as opposed to generalizing North America having one representative cold climate compared to a single representative cold European climate. Another interviewee stressed that with regard to climate, it was ultimately up to the designers to implement climate considerations into the building enclosure design. The interviewee felt that compared to other global markets, European building enclosure designers were more considerate of climate-related considerations in the design of the building enclosure.

Inappropriate design of a building enclosure for a specific climate can result in disastrous consequences. The most detailed document addressing the creation of the building enclosure to specific global climates was written by Bilow (2012), who analyzed eight cities located throughout the world and covering a broad range of climate types. The goal of the research was to create optimized facades that could provide high comfort levels and economic operations in various global climates.

**Local Capabilities**

Local capabilities refer to the abilities of design, production, and construction entities in a given region. Many interviewees stated that design and construction of building enclosures in international markets were constrained by local capabilities. One example mentioned is the shortage of skilled labor in developing regions. In the Far East, design knowledge for building enclosures is relatively sophisticated, but construction is usually carried out by unskilled laborers. Typically, these labor positions are low paying and the workforce is largely untrained. This leads to poor workmanship in the field, often resulting in the need for extra field supervision to achieve acceptable construction quality.

One interviewee stated that the Middle East is still maturing in its understanding of modern building enclosure. The interviewee recalled that the idea of a structural glass façade, (a building envelope component technology that integrates structure and cladding, and can be utilized in long-span applications where heightened transparency in the building enclosure is desired (Patterson 2011)) was largely unheard of in the Middle East, although such technology has been prevalent in North America and Europe since the 1980's. According to another interviewee, some building enclosure designs from North America had to be simplified for the local construction labor in order to be used successfully in the Middle East.

Limitations due to local capabilities were also seen in North America. It was often cited that European building enclosure sophistications were beyond those of most North American counterparts. Several interviewees stated that this could be attributed to Europe's well developed trade apprenticeship programs that train tradesmen and technicians to develop the skills necessary to construct building enclosures to meet European standards. These apprenticeship programs are not as prevalent in North America. Therefore, it is challenging to find North American building enclosure manufacturers and fabricators who are able to meet European standards. Products made in North America are typically sold in stock sizes to Europe, where they are fabricated to meet project requirements. Aside from skilled labor, it was also noted that the machinery utilized by European fabricators was not often found in North American fabrication shops. This inhibited North American fabricators from being able to fabricate European products due to the lack of appropriate equipment.

**Energy Costs**

Differences between energy costs in different global markets were a major factor cited for contributing to differences in the building enclosures as expressed in the interviews. The most prominent instance mentioned in the interviews was energy cost differences between North America and Europe. Many interviewees commented on the need to create building enclosures in Europe that would reduce the building's overall demand for energy. To meet these performance expectations in Europe, building enclosures often have higher initial construction costs than in North American counterparts. These higher costs are attributed to using more expensive building enclosure products and the presence of more sophisticated detailing, such as ensuring that thermal bridges do not exist anywhere in the building enclosure.

Energy costs often contributed to another factor for global difference: initial cost versus life-cycle cost. It was stated in the interviews that European developers are willing to spend more on the building enclosure if it results in a long term reduction in building energy consumption. This makes a property more attractive and easier to lease in an energy conscious population. Although North America is becoming more energy conscious, the energy savings payoff has yet to justify higher initial construction costs. Generally, European energy costs have been on the order of twice those in North America (Yudelson 2009). The lower energy costs in North America results in longer payback periods on energy efficient building investments relative to Europe. The tolerance for longer payback periods in North America is generally lower than Europe due to the higher presence speculative building developments. With an exception of Denmark and the United Kingdom, European real estate tends to be owner occupied compared to North America, which has a larger proportion of commercial buildings constructed for investment purposes (RREEF Research 2007).

One interviewee stated that greater emphasis was now being placed on life-cycle costs in the Middle East. This individual speculated that the number of projects with building enclosures consisting of highly transparent façades will decline as the Middle Eastern market becomes more aware of the need to save on energy. The Middle Eastern market is beginning to focus more on building operating costs as opposed to initial construction costs. This shift in philosophy will be articulated by creating building enclosures that save energy as opposed to creating architecture statements that are sometimes incongruous with the indigenous climate.

## CONCLUSIONS

Presented in this paper are factors contributing to global differences in building enclosures derived from eighteen interviews to date with building enclosure professionals who possess familiarity with multiple international markets. From the interview process, energy codes, local climate, local construction capabilities, and energy costs were the most prevalent perceived factors underlying why global differences in building enclosures exist. Each factor was reported to have an effect on the design and construction of building enclosures in different global markets. Identifying such factors and examining their roles in creating global differences in building enclosures will be of practical use for those wishing to conduct building enclosure projects in international markets.

## LIMITATIONS

The information that forms the content of this paper is based upon a preliminary sample size of eighteen interviewees as of September 2012. As more participants continue to be interviewed, the strength of the data will increase.

## ACKNOWLEDGEMENT

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# Hurricane Mitigation Design of Glazing Systems: Requirements for Wind and Windborne Debris Protection

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## ABSTRACT:

The perspective of this paper will be from the design requirements of the State of Florida, home to arguably the strictest and most complete building code requirements for hurricane design in the country. This paper will identify and address the requirements for glazing systems in the state that can be applicable to other hurricane prone regions of the country. The paper will also identify factors that help determine the capacity of glazing systems to achieve the goal of adequately protecting our buildings from hurricane force winds and wind borne debris during a storm. The scope of this paper is to raise awareness of the many aspects of glazing system design and materials with respect to hurricane loads in order to adequately mitigate damage to the buildings. This will be done by examining materials, code and all other compliance requirements necessary to achieve the above stated goal. The basic requirements in order to achieve the goal include: design considerations for wind and windborne debris protection, code and standards compliance, testing requirements, product certification, and inspection requirements. After reading this paper the reader will have a very good understanding of the issues pertaining to design of glazing systems to meet hurricane requirements and also have a good understanding of the entire process necessary to protect the building envelope from a powerful storm. In order for the glazing systems used in our buildings today to help mitigate the effects of hurricanes, all of the necessary steps mentioned above must be adhered to in the most complete way possible.

## KEYWORDS:

Glazing Systems, Hurricane, Wind Load, Windborne Debris, Hazard Mitigation

## INTRODUCTION:

Hurricane mitigation design of glazing systems in the state of Florida began in earnest after Hurricane Andrew exposed critical weaknesses in the building codes and installation methods with respect to glazing products. It was determined by the Florida legislature that the scale and magnitude of damage caused by Hurricane Andrew could have been mitigated with better building code guidance and oversight. Prior to Hurricane Andrew, there were numerous building codes adopted by the various municipalities in the state. After Hurricane Andrew, the Florida legislature decided to implement a unified building code for the entire state. Differences of opinion developed between areas most affected by the storm, South Florida (Miami-Dade and Broward counties), and the rest of the state. Miami-Dade and Broward counties had increased their building codes significantly based on research after the damage from Hurricane Andrew and also implemented much stricter guidelines on the design, testing and certifications of glazing systems. Municipalities in North Florida did not feel the need to strengthen their codes to the extent of South Florida. A compromise was reached in where Miami-Dade and Broward counties were allowed to keep their stricter code and compliance requirements within a new unified building code under a special region know as the High Velocity Hurricane Zone (HVHZ) which by definition includes only Miami-Dade and Broward counties. The essence of the HVHZ portion of the code is a strong reliance on design, testing and certification. Glazing products sold in the state of Florida must be designed, tested and certified as acceptable by one of its two approval agencies. Very little is left to rational analysis, once a product has been certified. The certification process includes very specific design pressure ratings and size limitations for the product being certified. Testing requirements are governed by a set of protocols developed by the Miami-Dade County. Product certifications, based on the above protocols, attempt to ensure that all exterior envelope glazing products sold in the state of Florida meet or exceed all mandated requirements. Special inspection requirements based on signed and sealed glazing shop drawings are required for threshold buildings. The State of Florida has the necessary tools in place to ensure a safe and secure building envelope if used and implemented properly.

## DESIGN CONSIDERATIONS:

When designing glazing systems in hurricane prone regions, there are two main loading considerations that must be addressed: wind and windborne debris. The designer must also be familiar with the code and standards associated with the primary design materials: glass and aluminum. In designing for the above mentioned loading considerations and materials, there are many additional design factors to consider including the product integration with the building substrate. Many of these design considerations are detailed and explained below based on the particular loading consideration (wind or windborne debris):

**Design Considerations for Wind Loading:**
The design wind load requirements are referenced in the unified Florida Building Code as governed by the American Society of Civil Engineers (ASCE) reference standard ASCE 7-10 (Minimum Design Loads for Buildings and Other Structures) using the Components and Cladding design procedures. Use of the simplified method or the use of a wind tunnel study to determine applicable design wind loads for a project is also allowed provided compliance is met with all requirements. These requirements are the same throughout the entire state. A more detailed explanation of the wind standard can be found in the proceeding section on Codes and Standards.

1. Uniform Design Load: The glazing products must be designed to sustain a uniform wind load to account for the forces associated with the sustained

hurricane force winds. These wind loads are applied to the building and glazing products as both positive and negative loads. The ASCE 7 wind load standard provides a method to convert the design wind speed into a design wind load (pressure) based on a series of factors. It is the design wind load that is used to analyze the adequacy of the product, not the design wind speed. Some of the factors used by the ASCE 7 standard, in additional to the design wind speed, in determining the design wind load are: building height, surrounding topography, roof type and risk factor.

2. Cyclic Design Load: The wind load forces during a hurricane include more than just uniform loads. The wind forces fluctuate greatly and include gusting and directional reversal loading including rapid positive and negative forces. To account for this, glazing products must be designed and tested to sustain cyclic wind loading as determined by Miami-Dade county testing protocol TAS 203 (Criteria for Testing Products Subject to Cyclic Wind Pressure Loading). A more detailed explanation of the cyclic load testing protocol can be found in the proceeding section on Testing Requirements.

3. Comparative Analysis: Since the essence of the revised codes of the state of Florida is a strong reliance on design, testing and certification, limited comparative analysis and not rational analysis is one of the few methods allowed to account for deviations in size or design load rating in the tested product with respect to the proposed product to be installed on a particular project. When a glazing product deviates from its overall size (frame width and/or height) or design load rating, special consideration must be taken to make sure not to exceed the tested parameters. Rational analysis is the process by which the designer uses engineering design principles to assess the adequacy of a structural member to sustain the applicable loads. Comparative analysis is the process by which the designer compares the effects on the proposed product (stress, deflection and load reactions) imposed by the proposed loads to the effects on the tested product (stress, deflection and load reactions) imposed by the tested loads. The stress, deflection and load reactions of the proposed products, based on the product parameters (load, width, height) cannot exceed those of the tested product based on the tested parameters (load, frame width, frame height). This method allows for size and load deviations while maintaining compliance with the tested parameters. When a product is designed, tested and certified to be sold in the state of Florida, it is issued a certification document or product approval. This product approval document lists all the necessary information needed to fabricate and install the product to assure compliance with the tested parameters. Very little variation is allowed with respect to overall product dimensions and installation. No deviation from the tested product with respect to material, product assembly, glass type, parts, etc is allowed.

4. Glass Strength: The path of the design wind load is typically transferred first and foremost though the glass, then unto the frame, followed by the anchors and ultimately to the building structure through the building substrate. Glass as a

material is very strong and capable of sustaining heavy uniform wind loads especially when heat treated. The glass types used on glazing products are:

a. Annealed: This type of glass is the basic glass type used on glazing products. It is not impact resistant and cannot be used in glazing products with safeguard requirements. The glass, when broken, breaks in sharp chards. It is used outside the windborne debris region when impact resistance is not required or within the windborne debris region when protected by impact resistant devices. Annealed glass is acceptable for use where low design wind loads are required.
b. Heat Strengthened: This type of glass is similar to annealed glass but develops two times the strength as annealed glass after undergoing heat treatment and can sustain much higher design loads.
c. Tempered: This type of glass is the basic safety glass and develops four times the strength as annealed glass after undergoing a more intense heat treatment. The glass, when broken, breaks in small cubes.
d. Laminated: This type of glass is the basic impact resistant glass. It is composed of a combination of two or more of the three previously mentioned glass types that are bonded together by an interlayer. The level of impact resistance is determined by the glass types, interlayer and number of glass sheets laminated together.
e. Insulated: This type of glass is the basic energy efficient glass. It is composed, in its basic form, by a combination of two of the first three glass types (a, b, or c) separated by a spacer that creates an air space between the sheets of glass.
f. Insulated-Laminated: This type of glass is the basic energy efficient impact resistant glass. It is composed by a combination of two of the first three glass types (a, b or c) separated by a spacer that creates an air space between the monolithic glass panel and a laminated glass panel.

The design of glass for uniform wind load is referenced in the uniform Florida Building Code as governed by the American Society of Testing and Materials (ASTM) reference standard E-1300-07 (Standard Practice for Determining Load Resistance of Glass in Buildings). A more detailed explanation of the glass standard can be found in the proceeding section on Codes and Standards.

5. Structural Silicone: For captured glazing systems, those in which the glass is mechanically secured to the glazing frame via a glazing pocket or pressure plate, structural silicone along with glass bite are critical components in securing the glass panel to the glazing frame. Two cases where this condition becomes critical are, under high uniform loads where the glass panel undergoes large deflections, and during cyclic loading after the laminated glass has sustained an impact and breakage has occurred. For two and four sided structural silicone systems where the silicone may be the only means of securing the glass to the glazing frame, the silicone used along with the glass bite becomes even more critical. For this reason, the allowable stress of the silicone under wind loading is typically limited

by code to 20 psi. In the rare case that four sided structural systems are not designed with dead load connectors to support the individual glass panels, most manufacturers, such as Dow Corning, limit the allowable stress of the silicone due to dead load to approximately 1 psi. In these cases, it is important to properly identify the effective glass bite used to determine the stress on the silicone.

6. Aluminum: Designing with aluminum can be very complex especially when dealing with the numerous different alloys, intricate shapes (extrusions), allowable stress reductions factors based on welding as well as slenderness and buckling limits. Adverse affects can be caused when interaction with dissimilar materials are overlooked. Designing with aluminum is referenced in the uniform Florida Building Code as governed by the Aluminum Design Manual.

7. Anchor Factors: More so than in any other industry, strict compliance with anchor design limitations is critical to the proper performance of glazing products. Anchor manufacturers publish design catalogs that provide the designer with allowable strengths (shear and tension). Strict compliance with the reduction factors due to spacing and edge distance limitations is very important as well as anchor performance into different substrates. Quite often a design is affected by the close proximity of a cluster of anchors with limited edge distance. An often overlooked design consideration for anchors is prying and bending forces created by connection details and typical methods of installation. Rational analysis is allowed on anchors provided that the design anchor capacity of the modified connection detail is equivalent or greater than the tested connections. This is due to the fact that most of the testing of glazing systems is performed with the systems being installed into wood test chambers.

8. Water Infiltration: The design of water infiltration ratings for glazing products is based on preventing water infiltration when the product is subjected to 15% of the wind driven rain caused by the positive design wind load.

9. Building Substrate: It is very important to understand and work with the structural engineer of record with respect to the loads imposed by the glazing systems on the main building structure to assure that they have been properly designed to sustain the forces. Often times the transfer of forces from the glazing system to the main structure is carried out by secondary elements such as steel framing or metal stud framing. These elements require specific attention. The loads imposed by the glazing system can often times be extremely high concentrated loads and if they are not brought to the attention of the structural engineer of record it could lead to structures that are inadequate to transfer the loads properly to the main building structure. This was the case during hurricane Andrew where bulkheads of metal stud framing were provided to support the loads of the glazing system without taking into account concentrated loads and bucking affects on the metal studs caused by such loads. Another drawback in using metal stud framing is the very thin nature of the metal framing with respect to the thread spacing on a typical sheet metal screw. Typically, proper backing is

required to provide the anchor sufficient embedment to develop adequate tensile capacity when installing glazing systems to metal stud framing.

10. Tributary Areas: When designing or performing rational or comparative analysis on glazing products it is important to use the tributary area applicable to particular structural member n question. Often times design engineers or architects use the design load associated with the tributary area based on the glazing products overall dimensions and not the individual structural element in question.

11. High Velocity Hurricane Zone (HVHZ): The HVHZ is a special region designated in the Florida Building code that by definition encompasses Miami-Dade and Broward counties only. This region is subject to stricter design, testing and certification requirements for glazing products than the rest of the state.

**Design Considerations of Windborne Debris Loading:**
The requirement for the design of glazing products for windborne debris loading is specified in ASCE 7 via a special map that identifies a windborne debris region. This region varies based on the design wind speed based on specific risk factors.

An instrumental part of impact resistant glazing systems is the glass interlayer. It is what bonds the multiple sheets of glass together and allows them to remain adhered even after impact and breakage, preserving the integrity of the building envelope. Interlayer are available in different thicknesses/types and different degrees of impact protection, such as those mentioned in items 2 and 3 below, can be achieved by varying those parameters.

The Florida building code requires that all products that are required to meet wind borne debris requirements comply with one of the following categories:

1. Impact Protection Devices: Impact protection devices include hurricane shutters wind screens, and any other device that has been tested and complies with the impact and cyclic load requirements of the Florida Building code under test protocols TAS 201 and 203. A more detailed explanation of the test protocols can be found in the proceeding section on Testing Requirements.

2. Small Missile Impact Resistant Glazing Products: For building envelope or protection devices to be installed above 30 ft of grade.

3. Large Missile Impact Resistant Glazing Products: For building envelope or protection devices to be installed up to 30 ft of grade.

## CODE AND STANDARDS COMPLIANCE:

The Florida Building code is the basis for design and provides the minimum design requirements for glazing system. The building code uses, by reference, material standards for glass and aluminum, among other materials, that govern the design of glazing products as well as wind load requirements. The current applicable building code and standards in the state of Florida are:

**The Florida Building Code:** The current edition is the Florida Building Code 2010. The pertinent sections of the code relating to design for glazing systems are Chapter 16 (Structural Design), Chapter 17 (Structure Tests and Special Inspections), Chapter 20 (Aluminum) and Chapter 24 (Glass and Glazing).

**The American Society of Civil Engineers (ASCE) Reference Standard ASCE 7-10 (Minimum Design Loads for Buildings and Other Structures):** The ASCE 7 standard is referenced in the Florida Building Code as the applicable wind load standard and has recently been revised. It is important to understand the changes (De La Guardia, 2011). The standard provides the basis to determine design wind loads, define hurricane prone regions and specify impact protection requirements of glazed openings for wind borne debris regions. There are radical changes in the organization and philosophy of the new edition of the standard, ASCE 7-10, from ASCE 7-05 and previous editions.

First it is necessary to understand the organizational changes in the standard. The new edition utilizes 6 chapters (Chapters 26-31) to disseminate the information that was previously encompassed in one chapter (Chapter 6). It places the general requirements in chapter 26 with the remaining five chapters covering the new modified design procedures. The design procedures have been revised from three previously "allowed" design procedures (Simple, Analytical and Wind Tunnel) into numerous "permitted" design procedures separated into two categories, Main Wind Frame Resisting Systems (MWFRS) and Components and Cladding (CC). The new "permitted" design procedures for MWFRS are: Directional Procedure (Chapter 27); Envelope Procedure (Chapter 28); Directional Procedure for Building Appurtenances and Other Structures (Chapter 29) and the Wind Tunnel Procedure (Chapter 31). Chapter 30 is dedicated to the new analytical design procedures for components and cladding (CC) (Parts 1 through 6), which are: Envelope Procedure (Parts 1 & 2), Directional Procedure (Parts 3, 4 & 5) and Directional Procedure for Building Appurtenances (Part 6).

The biggest philosophical change in the new edition of the standard is in how the buildings are categorized and the emphasis placed on impact protection of glazed openings. Previous editions of the standard have categorized buildings by occupancy with adjustments to the wind loads based on an importance factor associated with a particular building due to its occupancy. These occupancy categories and their importance factors did not address the impact protection of the individual buildings in question. Instead of utilizing the occupancy and importance factors of each building to determine impact requirements, the previous editions of the standard utilized a single wind speed per region to identify locations requiring impact protection. The new edition of the standard has devised new wind speed maps categorized by risk, putting a greater emphasis on impact protection as opposed to wind loads. Each new category is assigned different wind speeds that increase in speed based on increasing risk to the particular building in question. These new risk categories are a variation of the old occupancy categories but with an emphasis on risk instead of number of occupants of a particular building. The new edition of the standard effectively does away with the importance factor and instead incorporates this factor into the new wind speed maps based on Risk. There are now three different wind speed maps based on the new risk categories. Risk Category I (buildings and other structures that represent a low risk to human life in the event of failure), Risk Category II (all buildings and other structures except those listed in Risk Categories I, III and IV) and Risk Category III & IV (Buildings and other structures, the failure of which could pose a substantial risk to human life AND Buildings and other structures designated as essential facilities).

Another radical departure from the previous edition of the code is the emphasis on impact protection based on risk and not location. Whereas the definition of wind borne debris region remains the same with respect to location (within 1 mile of coastal mean high water line) the wind speed limits used to consider if the region is in the wind-borne debris region now depend on the risk categories. The new limit to determine if the region is in the wind-borne debris region is 140 mph up from 120 mph. However, the wind speeds now vary significantly based on the risk categories regardless of location. The biggest difference is that, whereas before the wind borne debris region covered all buildings within a specific location, now it is possible for buildings next to each other in a particular location to have different impact protection requirements based on their risk categories. The new risk factors, unlike the previous occupancy categories will affect both wind loads and impact protection requirements. The buildings that will see significant change are the ones in the higher risk categories in regions previously not considered to be in the wind borne debris regions. More of these higher risk buildings will be required to provide impact protection than in previous editions of the standard. Another significant change in the standard, with respect to wind loads, is that the wind speeds provided are now meant to be used with ultimate load (strength) design. To account for that change, the standard now allows a factor of 0.6 to be applied to wind loads when working with allowable stress design.

**The American Society of Testing and Materials (ASTM) Reference Standard E-1300 (Standard Practice for Determining Load Resistance of Glass in Buildings):** The applicable edition of ASTM E-1300 standard referenced in the Florida Building Code is E-1300-04e01. ASTM E-1300 provides the maximum uniformly distributed load that a glass specimen can safely withstand based on glass type, thickness, aspect ratio, load duration, intended use, boundary or support conditions and probability of failure.

**The Aluminum Design Manual:** The applicable edition of the Aluminum Design Manual (ADM) referenced in the Florida Building Code is the ADM 1-05 (Part 1-A: Specification for Aluminum Structures, Allowable Stress Design).

## TESTING REQUIREMENTS:

All glazing products that are sold to the public in the state of Florida must be tested to comply with testing protocols developed by Miami-Dade County code compliance department. The glass or product must still be operable and protect the building envelope after all three tests are performed. (De La Guardia, 2012)

**TAS 201 (Impact Test Procedures):** The large missile impact test criteria, under TAS 201, was developed and intended for building envelope products installed on elevations up to 30 feet of grade and consists of a 9 ft long, 9 lb 2x4 wood specimen launched out of a laser-guided canon at a speed of 50 ft per second impacting the glass or product three times. The small missile impact test criteria, under TAS 201, was developed and intended for building envelope products installed on elevations above 30 feet of grade and consists of a total of 30 solid steel balls each having a mass of 2 grams with a 5/16" nominal diameter launched out of a compressed air canon at a speed of 130 feet per second, delivered in groups of 10, impacting the specimen three times.

**TAS 202 (Criteria for Testing Impact and Non-Impact Resistant Building Envelope Components Using Uniform Static Air Pressure):** The uniform load test is performed by first applying one half (0.5) of the test load (test load equals 1.5 times the design load) then applying one half the reverse test load. This is followed by applying the full test load then applying the full reverse test load. Each of the above steps are followed by holding the load for 30 seconds then releasing the load across the specimen followed by a recovery period of not less than 1 minute nor more than 5 minutes between load reversals. All readings (deflection and permanent deformation) are recorded at completion of each imposed load. The water infiltration test is part of the protocol and is performed by delivering and maintaining a water spray at a minimum rate of 5 gph per sf, applied at a pressure equal to not less than 15% of the positive design load. The pressure and water spray is to be maintained for a period not less than 15 minutes. No water infiltration shall occur.

**TAS 203 (Criteria for Testing Products Subject to Cyclic Wind Pressure Loading):** The cyclic load test criteria, under TAS 203, involves a total of 4500 positive and negative load cycles with a minimum duration of one second per cycle. The cyclic load test is intended to simulate the variations in pressure during a storm and is applied to the test specimen and glass AFTER it is impacted.

## PRODUCT CERTIFICATION:

There are currently two product certification agencies in the state of Florida, the Miami-Dade County product approval agency and the State of Florida product approval agency. Miami-Dade County upgraded their entire product approval process in 1994 as a result of lessons learned after Hurricane Andrew struck South Florida in 1992. In 2003, the State of Florida created an alternate product certification agency. Once a product has been designed and tested it must obtain certification by one of the two agencies.

## INSPECTION REQUIREMENTS:

Inspection is the final opportunity to ensure a safe and secure building envelope is provided based on all the above mentioned requirements. A proper inspection can only be performed based on a properly prepared set of shop drawings prepared by a licensed professional engineer. A properly prepared set of shop drawings should include:

1. The complete design criteria
2. A well detailed floor plan along with sections and elevations.
3. The glazing product manufacturer name and series.
4. The Miami-Dade County or Florida product approval number
5. Whether the glazing product is non-impact or impact rated along with the impact rating (small or large missile) and if whether or not shutters are required.
6. The allowable glass type and thickness (based on the product approval) along with the exact glass composition including allowable interlayer type and thickness (if laminated impact glass).
7. Framing connection details integrating the system with the proper and actual building substrate including anchor type, spacing and edge distance limitations.
8. Product framing/extrusion details including any internal member/mullion reinforcing with exact reinforcing levels and locations.

A proper inspection entails identifying any field conditions or deviations from the approved drawings and immediately bringing it to the attention of the design professionals. Examples of typical installation deficiencies include:

1. Excessive shimming of connections causing eccentric loading or bending forces on anchors.
2. Not adhering to anchor edge distance and spacing limitations
3. Installing framing into substrate not depicted in the approved shop drawings.
4. Substitution of glass types from those specified on the approved shop drawings.
5. Improperly attached wood bucks.
6. Inadequately designed metal stud framing.

## COMPARISON TO OTHER STATES:

The International Code Council (ICC) develops Model Building Codes which individual states, and municipalities within states, use as basis for their own codes. The intent of the ICC Model Building Codes is to unify the building codes across the country and provide states with the most up to date minimum design requirements based on the latest research. More important than unifying building codes around the country is unifying building codes within a state. It is very difficult to provide oversight and ensure proper design when each municipality within a particular state is allowed to adopt different and potentially conflicting and outdated codes. The Model Building Code most applicable to the topics presented in this paper is the International Building Code (IBC) which is one of the primary codes that Florida, as well as most of the other states in the hurricane prone region, uses as the model for their building code. The IBC also references the previously mentioned ASCE 7 as the applicable standard for designing for wind loads. As previously mentioned ASCE 7 contains a map that outlines all hurricane prone regions in the country. ASCE 7 also defines and specifies the windborne debris regions within the states. Therefore, the Florida Building Code should not be radically different in terms of designing for wind loads then the other building codes in the states within the hurricane prone region. The states, other than Florida, that are located in the hurricane prone regions of the mainland United States include: Texas, Louisiana, Mississippi, Alabama, Georgia, South Carolina, North Carolina, Virginia, Delaware, New Jersey, New York, Maryland, Connecticut, Rhode Island, Massachusetts, New Hampshire and Maine. According to a report by The Insurance Institute for Business & Home Safety (IBHS) titled "Rating the States: An Assessment of Residential Building Code and Enforcement Systems for Life Safety and Property Protection in Hurricane-Prone Regions", many of the states in the hurricane prone regions did not score well. The report is based on research in three areas that, according to IBHS, are critical to ensure proper protection in states within hurricane prone regions. The three areas of focus were: providing a unified Model Building Code for the entire state, code official certification and contractor licensing. The report ranked the eighteen states in the hurricane prone regions on a scale of 0 to 100. Florida (95) ranked the highest. Eight of the eighteen states: Georgia (66), Maine (64), New York (60), New Hampshire (49), Alabama (18), Texas (18), Delaware (17) and Mississippi (4) scored a 66 or less, with the last four states not having adopted a unified state code. What sets Florida apart from the other states is compliance and enforcement of the code along with the additional unique glazing requirements, not identified in the IBHS report, of product testing, certification, and the requirement of engineered shop drawings for glazing systems. Only one other state, Texas, has its own product certification agency, via the Texas Department of Insurance, and that certification process is voluntary and tied in to the state insurance program. It is critical for the other states in the hurricane prone region to take head from states such as Florida, who have experienced a powerful hurricane and implemented measures to mitigate future damage, and strengthen their codes with respect to glazing systems before a powerful storm hits.

## CONCLUSION:

In order to achieve the goal of a safe and secure building envelope capable of sustaining and successfully mitigating damage caused by hurricanes, it is essential that all of the above requirements are satisfied. A break in any of the criteria mentioned in the paper (design considerations for wind and windborne debris protection, code and standards compliance, testing requirements, product certification, and inspection requirements) could have catastrophic effects on the performance of the glazing system.

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# Standardisation of Building Information Modelling in the UK and USA: Challenges and Opportunities

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## Abstract

Standardisation provides an invisible digital infrastructure within which digital design technologies support coordination by heterogeneous actors in the construction sector. Inadequate standards pose challenges to design technologies such as Building Information Modelling (BIM). In its latest strategy mandating the use of BIM, the UK government blames the construction industry's lack of collaboration and inefficiency on low levels of standardisation. This paper investigates the development of standards as invisible digital infrastructures for facilitating collaboration in construction projects in the USA and the UK. The paper draws on a) interviews with key standards development consultants in the UK and USA and b) industry publication and revisions to the British standard through the publicly available specification (PAS) 1192 and NBIMS in the USA. The literature on standardisation suggests that engagement in standard development is often motivated by self-interest; and that standards are developed through consensus building, political processes of aligning multiple standards, and end-user participation. Findings from the empirical work to date suggest a rapid process of development, excessive self-interest, minimal end user participation and incompatible processes. The study concludes with observations on how digital infrastructures develop and could be useful in shaping practice and how such artefacts are integrated in dynamic, unstructured and rapidly developing project based environments. The paper contributes to literature on evolution and proliferation of digital infrastructures in sectorial systems of innovation.

**Keywords**:

BIM, Invisible digital infrastructure, Sectorial systems of innovation, Standards, Standardisation

## Introduction

Invisible infrastructures become embedded into the fabric of socio-technical systems through complex processes of interaction between diverse actors. These complex processes produce changes through modifying the network's behaviour, culture and processes of collaboration between actors (Hanseth and Monteiro, 1997, Bowker and Star, 1999a). Standardisation of digital design technologies, as a process of embedding invisible digital infrastructures formulates coherent platforms upon which actors interact in delivering building projects. Collaboration during the building process is complemented by the development and deployment of artefacts, that determine the rules of engagement between professional domains (Bouchlaghem et al., 2005). This study investigates the current efforts in developing Building Information Modelling (BIM) process standards as an open shared digital infrastructure for information exchange between diverse teams.

Social studies characterise standards as invisible infrastructures that support coordination and interaction in society (Star, 2002). Such infrastructure becomes embedded and 'substrate to events and movements,… is invisible and *forms* the background of other kinds of work' (Lampland and Star, 2009 p.17). They posit that even though standards are not immediately visible in social interaction they provide the social fabric or infrastructure that moderates and support social interaction. Digital design technologists describe standards as digital objects that facilitate interoperability and exchanging of information between design systems (Eastman, 1980, Eastman et al., 2010, Björk and Laakso, 2010). Research in digital design technology standardisation has so far centred on : a) technical functions in the exchanging of design information in Computer Aided Design (CAD) models between design domains (Fu et al., 2006, Sanguinetti et al., 2012) b) enabling infrastructures and system component libraries and, c) 3D object based visualisation systems (Barghouti and Kaiser, 1991, Fu et al., 2006, Sanguinetti et al., 2012). Less is known on the development and enactment of process standards, even though they are important in facilitating information exchange between communities of practices.

Standards Development Organisations (SDOs) such as the British Standards Institution (BSI), (UK), National Institute of Building Sciences (NIBS), (USA) and buildingSmart alliance, have been facilitating initiatives to create process management artefacts for use in project based environments (NBIMS-US, 2012). The recent publication of PAS 1192 (UK) and NBIMS (USA) is testament to such efforts (Bimtaskgroup, 2012, NBIMS-US, 2012, Wikipedia, 2012). The COBie standard for use in through life built asset management is also under development (NBIMS-US, 2012, buildingSmart, 2012, East, 2012). However the development and enactment process for the standards cited above has been marred by irregularities and criticised that, (a) the technology is still developing and yet standards are being rapidly progressed (b) there is inadequacy of supporting infrastructure e.g. COBie spread sheet compatibility with Excel; (c) the process is fractured and loosely coordinated and, (d) funding is scarce and driven by self-interest.

A sectoral system of innovation perspective suggests that, heterogeneous firms interact to generate, adopt and use technologies for the creation of sectoral products and services (Malerba, 1999, Gann and Salter, 2000). 'They interact in a market and non-market way through processes of communication, exchange cooperation, competition and command, and their interactions are shaped by institutions (rules and regulations)' (Malerba, 1999 p.4). However, such a perspective of the does not adequately explain the development of common shared digital infrastructures particularly digital standards and the effects posed on the firm and the sectors innovative activities. They also fail to address the effects of structured processes of interaction on individual firm's competitiveness and innovation performance of whole or parts of systems of innovation. Theoretical concepts on sectorial systems of innovation are insufficient to explain the process standardisation phenomenon in relation to challenges posed on the sectors' innovative capacity and actors' competitiveness. This paper investigates the various initiatives highlighted above, factors affecting them and the challenges posed on interaction between actors in the USA and UK sectoral systems of innovation.

The paper is divided into sections as follows. The second section provides a theoretical review of standards as invisible digital infrastructures embedded in sectoral systems of innovation. Section 3 analyses variables influencing the current digital design. Section 4 presents the research findings. Section 5 provides a discussion on the observed phenomenon. In conclusion, section 6 provides a summary, next steps and areas needing further research.

## 2-The conceptualisation of standards

The delivery of construction projects is a complex process and it involves social interactions between diverse actors (Cicmil and Marshall, 2005). Process standardisation provides a digital infrastructure for translating data across boundaries, especially in construction teams where lifespans are often short and temporary (Whyte and Lobo, 2010). Standardisation refers to, the process of enacting, absorption and implementing a standard for the purpose of enhancing interaction between different parties (Björk and Laakso, 2010). Standards have influence on people's practices and they shape practices (Monteiro et al., 2012). Literature suggests that standardisation is a complex process that can only be achieved through meticulous negotiations (Hanseth and Monteiro, 1997, Bowker and Star, 1999b). Brunsson et al (2000) suggests that because standards have an influence on society, as they are developed through political processes of negotiation, society relies on them to manage diversity. The objective of standardisation is to ensure coordinated actions and an even operating platform within which everyone involved is conversant. Monteiro et al (2012) defined standardisation as, "the process of meeting similarities in demand". Standardisation ensures the maximisation of gains from collective action. As a result formal communication becomes less relevant as social action becomes easily predictable, thus fully exploiting the benefits of networking, coordination and predictability of actions (Brunsson and Jacobsson, 2000, Lampland and Star, 2009). Brunsson and Jacobsson (2000) suggested that organisations and humans are embedded in society, therefore they are susceptible to the rules that govern society, in particular standards.

The concept of invisible infrastructures describes standards as the, 'invisible glue that binds disciplines together, within and across their boundaries' (Star, 2002). As discussed in the work of Whyte and Lobo, digital infrastructures encompass digital objects, maps, models, drawings, standards and repositories (Whyte and Lobo, 2010). Digital infrastructures coordinate knowledge use and management across professional boundaries. This type of infrastructure is similar to that described by Star (2002) as social goods that support collaboration across boundaries. In Star's work these infrastructures are described as invisible artefacts that only become visible as a result of interactions with actors in specific contexts (Lampland and Star, 2009). Although the composition and functions of the infrastructure have been investigated, less is known about their development, factors that influence enactment and diffusion in networks of interactions between diverse firms.

Standards, like physical infrastructures require constant maintenance to remain relevant with other systems. Incompatible standards are not only a risk to the transfer of knowledge between professional domains, but they threaten the development of new practices (Choi et al., 2004). Standards attract different meanings in different contexts; they are a relational concept and flexible enough to allow selective interpretation (Lampland and Star, 2009). Because they facilitate and restrict interaction between heterogeneous actors they determine the texture of the network. To date there has not been enough empirical effort to examine them in this context. Although the general characteristics of standards are acknowledged in literature, the factors that influence such characteristics have not been significantly analysed.

Sectoral systems of innovation literature suggest that firms rely on networks of relationships to develop, adopt and use technology to advance innovative activities which are considered crucial for their survival (Malerba, 2005). Choi et al observed that, "firms rely on interconnectedness and standards to survive" (Choi et al., 2004). This interconnectedness can be considered as a way for people and technologies to harmoniously interact, especially in specific and self-repeating contexts (Brunsson and Jacobsson, 2000, Lampland and Star, 2009). Standards provide a platform for distributing knowledge within systems of innovation (Edquist, 1997). They provide a platform for sharing and distributing knowledge across diverse settings (Hanseth and Monteiro, 1997). They are a form of expert knowledge stored in rules and behaviours (Brunsson and Jacobsson, 2000). Edquist (1997), observed that standards provide an environment in which alternative proposals and incremental adaptations incubate. The factors that give rise to such characteristics and their influence on the development of systems of innovation are less acknowledged especially construction teams where interactions are short-lived and temporary in nature.

## 3 – Research setting and methodology

### UK and USA industry overview

The UK and USA construction industries are vast, dynamic and diversified. In the UK the industry contributes £110bn annually to the economy's Gross Domestic Product (GDP). 40% of its annual turnover is from government investment, and government is a key employer (CabinetOffice, 2011b). As a major employer, the government has large programmes for delivering new hospitals and schools through the private finance initiative (PFI) and major projects such as the London 2012 Olympics, the Cross rail and High Speed Rail 2. In the USA, the industry contributes $989bn annually (2010 figures) to the economy's gross domestic product (BEA, 2012). The industry employs 5,5million people, (as of 2010). In 2010 alone the US government spent $275bn on construction projects (U.S.CensusBureau, 2012, bls, 2012). In the UK, the industry employs 2.04 million people. The industry has been severely affected by the prevailing economic down turn (Maer, 2012). Throughout the late 1990s and early 2000s, the UK industry was the focus of significant initiatives aimed at process improvement by learning from other industries and international best practices (e.g. Egan, 1998, Fairclough, 2002, Latham, 1994) ). The UK government has signified its commitment to streamlining procurement processes in its latest construction strategy (CabinetOffice, 2011a). Low levels of standardisation have been suggested to be exacerbating waste generation and inefficiency in construction processes (CabinetOffice, 2011a).

The process of standardisation is systemic. It involves constant cooperation, interaction and relies on complex relationships between networks of actors with particular interests in safeguarding their self-interests. Investigating the drawing of digital infrastructures requires a systematic dissection of their evolutionary processes (Star, 1999). In this study, the first step was to undertake a desk study, to review current publications, standards, etc. on the process standardisation of BIM. This provided vital information on the wider debate around BIM standards and the actors involved. A number of variables were identified from these publications as presented in Table 1 below. The second stage was a follow up with detailed interviews with some actors in the industry. These were selected on the basis of their involvement in the current BIM process standardisation initiative. In order to understand the prevailing practices and discourses the authors also attended a number of industry wide BIM conferences and seminars. Through these detailed field studies the authors were able to develop a deeper understanding of the phenomenon. The study draws from documents and other publications on BIM standardisations in both the UK and USA. These publications were important to provide a wider understanding of the impact of BIM standardisation across the two countries. In order drill down into the issues identified in stage 1, eight semi-structured interviews were conducted with some of the key actors in the construction sector, particularly those directly affected by BIM process standards. These were leading BIM standards development consultants, representatives of SDOs and end users based in the UK and USA (most of them in UK). The interviews were used to examine in detail the issues raised in the publications (variables). The interview data was analysed using the Nvivo software.

**Factors influencing the standardisation process**

**Table 1: Overview of US and UK BIM standardisation characteristics**

| Variable | United State of America (USA) | United Kingdom (UK) |
|---|---|---|
| **Funding** | Standards development partly funded through NIBS. Part of the funding is generated through buildingSmart – an alliance of private software development companies. Funding is mainly through sponsorship by software organisations. | Privately funded through BSI, Part of the funding is through buildingSmart – an alliance of private companies. CIC partly funded by government. |
| **Research & Development** | Minimal participation in process standardisation. Research predominantly in technical standards | Some participation in process standardisation. Focus mainly on technical aspects of BIM. |
| **Process of standards enactment** | Open standards development processes. Development managed at regional and national level. | Open standards development processes. Development managed at national level. |
| **Software Developers** | Autodesk, Bentley, BIW, 4Projects Participation mainly through buildingSmart alliance. | Autodesk, Bentley, BIW, 4Projects. Participation mainly through buildingSmart alliance. |

| | | |
|---|---|---|
| **Political intervention** (Government) | Indirectly through NIBS, the US National BIM Projects Committee and GSA. BIM standardisation is managed by the NIBS-buildingSmart alliance. 22 regional government agencies, some are not members of buildingSmart. | Government set up BIM task group to facilitate the development of BIM standards. Through the CIC government setting up regional BIM hubs. CPC oversees BIM strategy and BIM standardisation. |
| **Role of SDOs** | NIBS-buildingSmart alliance facilitating standardisation. Process supported by some government agencies. The 22 regions have different systems. Some are not part of buildingSmart. | BSI main SDOs facilitating meetings between stakeholders. buildingSmart (UK and Ireland chapter) supports BSI in developing standard. MOU between buildingSmart UK and USA. |
| **Proposed BIM Standards** | National BIM Standards Version 2 published summer 2012. National CAD standard. COBie integrated into NBIMS. COBie useful in facilities management. | PAS 1192 – collaboration management standard, sets out information management protocol. PAS 55 – Asset management. COBie in progress. |
| **Participation of Users** | Major users of BIM standards are those participating in the development process. These are contractors, design firms, private and public organisations. Participation through membership of NIBS. | Major users of BIM standards are those participating in the development process. These are contractors, design firms, private and public organisations. Open participation. |

In the next section we review the above variables in the context of their effect on the development of national BIM process standards in the USA and the UK.

## 4 – Research findings

### Learning and knowledge sharing between actors

The relationship between actors in the network prevents or encourages the adoption of uniform protocols for exchanging project information. Standards underpin the full utilisation network benefits, in that they foster knowledge sharing, and encourage the maximisation of economies of scale during construction. However the current standardisation initiative is failing to gain trust by key actors. As one of the interviews at a BIM COBie conference observed,

> It's about the politics …, it's to do with the lack of trust …, and it's about a culture of securing your exploits and divulging less, than the industry for you.

The relationship between actors within a system of innovation is vital for the stability of the network (Edquist, 1997). The current initiative lacks trust from actors hence gathering a collective around the initiative is difficult. Without enrolment of the key actors responsible for project delivery, the standard risks being shun by practitioners. The challenge is therefore in establishing trust between traditionally rival actors. Even though standards might genuinely be intended at supporting collaboration and functional responsibilities, their effect is significantly compromised if they are perceived to be redistributing the exploits of competitors within the system. This might explain why confidence and participation in the process has been abysmal especially in the USA. As observed by one interviewee,

> It's too early to see how useful it is. Even in the US although there has been talk about the standard for some time, all people know is some people out there are developing BIM standards. How exactly it's going to be used nobody knows (Interview, bims12)

Literature on digital infrastructures suggests that they are the aesthetics, justice and change management apparatus of systems (Star, 1999). Even though infrastructures provide the system with the integrity and rigidity to span across boundaries of practice, their development rely on trust and active cooperation between actors. Trust and confidence in the process was found to be particularly lacking in both countries.

**Identifying stakeholders to participate in process standardisation**

Identifying the key actors in the construction system of standardisation is an important part of the standardisation process. The study noted that excessive influence by some actors is affecting the enrolment of other actors in the current initiative. BuildingSmart has been particularly versatile and leading in the development of standards for CAD and BIM in the USA and UK, however the perception by some in the sector is that it belongs to the Information Technology (IT) sector and thus serves its only interests more than the sector's collective interests. BuildingSmart is composed of actors from diverse back grounds. These include among many, government agencies and software developers. The more active ones are software developing firms. It was instrumental in the sponsoring of the Industry Foundation Class, STEP and CAD standards (buildingSmart, 2012). Its ability to mobilise support from small building contractors and lead the current initiative has been weakened as some of the small constructor's firms are not participating. The bureaucratic nature of the process means time is lost and there is not enough participation by all actors. This leads to inferior standards or no standard being adopted at all, thus potentially affecting rates of innovation in construction firms. One interviewee noted,

> If you have a negative vote, you have to resolve that negative vote before you can move forward and one of the problems with that is you can have one person block the entire standard from having it implemented. … I have seen instances where that's taken more than 5 years to have that one problem resolved. That's why we have voted not to have that in our (buildingSmart) rules of governance. (Interview, bims14)

Invisible infrastructures need to be integrated into the network for them to deliver desired benefits. This provides the integrity and rigidity required to span across boundaries. Efforts to develop common systems of practice might be shunned as a result of rigid processes of developing BIM process standards. This could affect the enrolment of actors in the initiative. Lack of participation is symptomatic to fears attached to such concerns. Although the current process is open for participation by all, there is no consensus on the benefits to the wider system.

> You have attributes that's too many and the worksheet is not manageable and I am giving you a conservative estimate. I am a technologist; I can't get my head around why they have chosen a technology that does work. …, but the likes of … does not understand that it does not work and he is driving it but you talk to …knows that it does not work. So there is this kind of disconnect between groups. (Interview, bims10)

A few actors have created small communities that wield influence over the whole process. Financial sponsorship is from large software development firms that have financial interest in the process, especially that they will be responsible for developing software to manage information exchange. There is less support from end user actors such as constructors and designers. To the extent that end users feel their contributions are not given the importance they deserve.

**Incompatible infrastructure**

The COBie standard's incompatibility issues are reminiscent of a digital infrastructure which is unable to integrate and descent into invisibility without affecting normal functioning of other infrastructure. As one frustrated Interviewee explained,

> We are in (a) situation where they have tasked Autodesk with reading Revit models and producing COBie now everything in your models comes out on your COBie sheet and then its driven by the computer and there you have got a in a decent size job you have got a million rows and I keep on going back to the Mechanical and Electrical rows,… So you can't maintain a million things in excel. (Interview, bims10)

Therefore the incompatibility between the new and existing infrastructure is affecting the development of process management artefacts for use by actors in the sector.

## 5– Discussion

This exploratory study has sought to investigate the factors influencing digital infrastructures and their functions in sectoral systems of innovation. Challenges of embedding digital infrastructures in immature systems have been identified. The political processes of setting up standards have been highlighted, however their development processes especially on when they should and should not be visible still need wider debating and detailed examination. Invisible digital infrastructures support the functioning of systems; however they also require meticulous efforts in preparing platforms upon which they operate (Star, 1999).

Conceptualisation of their influence on other infrastructures is important to understand how they help protect an individual firm's competitiveness while at the same time ensuring maximum participation in developing social infrastructures. The research assumes a sector level analysis and does not seek to generalise across the construction industry. Could the results be the same at firm and project levels? This research prepares the ground for a much wider study into the development of standards and how the processes impact on the exploitation of the full potential in systems of innovation.

The study observed that the UK has one SDO in the BSI whereas the USA has a number of SDOs. The USA sector is divided into 22 regions and each region operates autonomously. As a result, it is difficult to obtain participation of all the different regions, could this have an effect on the creation and adoption of standards? The UK construction sector has approximately 170000 organisations whereas the USA's has approximately 980 000 organisations, this might have an impact on the functioning of the system of innovation and the development of shared artefacts for regulating interactions between actors in the system.

## 6- Conclusion and next steps

The involvement of software vendors from the IT industry presents opportunities in the form of new knowledge, financial sponsorship and practices for accomplishing standardisation. Negative consequences are, they leverage significant influence over the process and end user suggestions are still suppressed. The process seems insufficient to withstand the challenges in large sectors where government support is limited (e.g. USA).

Even though BIM has been embraced internationally the two countries still have different approaches. In the USA emphasis appears to be devoted to the interoperability and the transfer of information between models (NBIMS), while PAS1192 address process standardisation. Although both standards are vital their importance to the sectors is still unclear. The concept of the digital infrastructure may be useful to understand the nature of interactions between actors in systems of innovation. However a lot still needs to be done to understand their role in learning, coordination, collaboration and knowledge transfer between heterogeneous actors. This study has so far been consigned to sectorial systems of innovation, future studies will investigate what their functions might be, how they are prescribed, when and how they get embedded in systems of innovation.

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# DE-NORMALIZE IFC MODEL FOR DATA EXTRACTION

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IFC (Industry Foundation Classes) has been widely adopted in BIM (Building Information Modeling) for information interchange. Actual data exchange relies heavily on the IFC support of target application. This paper introduces a generic way of accessing IFC model business data as needed. In this paper, we will present 1) a concept and a method to define tabular views of IFC data for downstream uses, 2) an algorithm to transform IFC data to defined tabular views, 3) a tool of exporting transformed results to ODBC compliant applications e.g. MS Office etc. in the context of i-model, a self-describing, read-only graphic container containing information with engineering precision, and 4) a case study to create COBie handover from IFC using this tool.

BIM, COBie, IFC, i-model, Interoperability

## INTRODUCTION

IFC (Industry Foundation Classes) has been widely adopted in BIM (Building Information Modeling) for information interchange. Actual data exchange relies heavily on the IFC support of the target application. Each application consuming IFC data implements its own IFC plug-ins. As more and more data are modeled in IFC, a need arises to interoperate with business applications such as MS Excel. Given the large amount of business applications and their various purposes, getting business applications to support IFC seems to be a stretch. In this paper we experiment with an approach to make IFC data easily accessible from business applications. We will discuss the challenges and solutions in our experiment.

One challenge to get IFC data into business applications is the different modeling techniques. Objects and object relationships are used in IFC model where tabular relational data are the main format in business applications. We attempt to bridge this difference by creating tabular views of IFC model. To accomplish this, we designed a data structure called a D-Tree to store the view definition.

As many other modern information modeling technologies, IFC schema is complex and highly normalized. It is structured this way for a number of very good reasons: schema flexibility, easy maintenance and minimal data duplication. While getting high level tabular views of the data can be done by querying the model, the queries required to extract information of interest are extremely complex and require specialized training to use effectively. In this paper we will discuss an algorithm to decompose tabular view definition into queries and assemble the query result into a table. We call this process de-normalization.

Another challenge to interoperate with business application is to make the tabular views available. We need to use well-known open interface which are already supported by business applications. In our research we selected the ODBC (Open Database Connectivity) interface. ODBC is a middleware API for accessing database management systems (DBMS) and is supported by most business applications. Making this IFC tabular view exposed via ODBC enables ODBC compliant applications access these views natively.

The third challenge is to obtain the schema of an IFC model. We need the schema that an IFC model uses to trace the classes and their relationships. To achieve this, we used Bentley i-model, a self-describing, read-only graphic container containing information with engineering precision. It may contain 2D and 3D geometry as well as business objects and properties. Any required schema is embedded in an i-model. No application logic or proprietary code is required to display and query its contents. In our use, any i-model containing IFC data has IFC schemas embedded.

## DEFINE TABULAR VIEW OF IFC MODEL USING D-TREE

A tabular view definition specifies columns and rows of a view. It is represented in a data structure called D-Tree. An example of D-Tree is given in Figure 1. Each node represents an IFC class. Related classes are connected to each other to provide the information needed for a tabular view. Each edge is specified by a relationship that links the two IFC classes together.

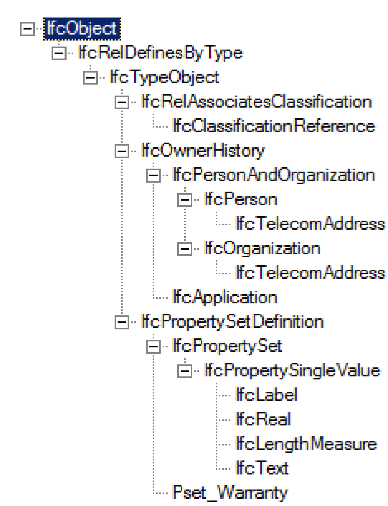


Figure 1: An example D-Tree

The top class or root node specifies which instances to start the de-normalization and thus defines how the rows are generated. Row definition is implied by the tree structure, which includes topology of the tree, relationships represented by the edges, and de-normalization algorithm. In this section we will focus on column definition.

### Basic view column definition

View columns come from IFC class properties. These columns may come from multiple classes in the tree. In many cases, not all properties of the classes in a D-Tree are needed in the view. For some classes like those starting with IfcRel, which are used for modeling relationships, their properties may never be of interest to define a view. D-Tree stores the properties and their classes that are selected to be the columns.

The column type can be inferred from the type of class property. The column name can be set manually or use the name of class property.

**View column pivot and roll-up**

There are two special cases in the view column definition: pivot and roll-up. They are related to IFC modeling techniques.

The first case is that the IfcRelDefinesByProperties class is used widely in defining properties in IFC models. Take an example of IfcSpace class shown in Figure 2, its area and height property may be defined through IfcElementQuatity, and the value of the property is defined by other classes like IfcQuantityArea. These properties are not properties of a class in the IFC schema and yet they are properties of an IFC instance in a particular IFC model. These Instance Properties are dynamic and we don't know if they exist until we open an IFC model and inspect it. They would show up as rows in our view if we don't handle them differently.

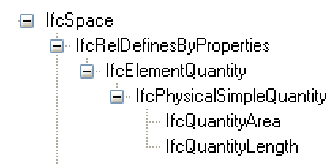


Figure 2: Instance Property

Conceptually, Instance Properties are not different from the Class Properties and could be of interest for reporting in the columns of a view. For these Instance Properties to be on the columns of a view, we introduced Pivot definition in D-Tree. Pivot can be thought of as applying a matrix transpose on a table which moves Instance Properties from rows to columns. In other words, with Pivot definition we will move the defined potential properties from rows to columns if we find them.

Four attributes are needed to make up a Pivot definition:

- Row ID, which defines ID used for a row. For example, Name in IfcSpace in the above sample.
- Pivot Column Name, which defines where we can find the names of dynamic properties. For example, Name in IfcPhysicalSimpleQuantity in the above sample.
- Pivot Column Value, which defines where we can find the values of dynamic properties. For example, AreaValue if IfcQuantityArea or LengthValue in IfcQuantityLength.
- Pivot Value Operation, which defines how we deal with the values of a dynamic property. The operations can be: Sum, Average, Count, Min, Max, etc.

The other case is that IFC schema uses different names for a conceptually single column in a view. For example, the value in IfcQuantityArea is called AreaValue while the value in IfcQuantityLength is called LengthValue. These different names would end up in different columns, which is not desirable for reporting. To resolve this issue we introduce a Roll-up definition to merge conceptually similar columns.

A Roll-up definition is described by the following grammar:

<start> -= <entry> | <entry> ; <start>

<entry> -= [target] : <properties>
<properties> -= [property] | [property] , <properties>

Where <start> is the start symbol, <entry> is symbol representing a column-value map, <properties> is a symbol representing the values to be used for a column, [target] is the string specifying the name to merge to, and [property] is the string specifying names to be merged from.

## TRANSFORMATION ALGORITHM

The transformation algorithm is used to transform IFC model data into a tabular view defined by D-Tree. A series of queries are generated automatically based on D-Tree and executed. Query results, which are the instances of each class in the D-Tree, are chained to produce the view. An overview of the transformation algorithm is as follows:

1. Given the D-Tree, start at the root node and query for each of its instances.
2. For each instance, query the next instance related to it or in the path so far.
3. Repeat step 2 for each of the next related instances found in the D-Tree until all classes have been accounted for.
4. A path found from a root instance to the end represents a single row in our initial table. The specified class property values from each instance are then extracted to fill that particular row.
5. Apply Roll-up and Pivot transformation.

**Decompose D-Tree into queries and assemble results**

Once the D-Tree is provided, it is flattened into a list by running a graph search starting at the root node. The order in which nodes are visited is the order of the nodes in the list. In the simple D-Tree shown in Figure 3, this list ends up being the same in structure as the tree itself. A more complex example is shown in Figure 4 in which one branch is explored before the other. This list structure represents the order in which related classes are queried. This structure is used in looking up which instance to be the starting point when looking for the next related instance. For the example in Figure 4, class D is related to class A rather than class C; instances of A can always be found at the beginning of the list when it comes time to run the query for instances of D.

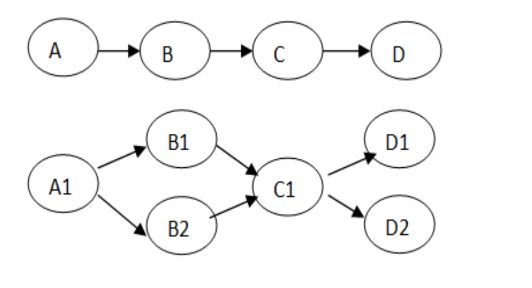


Figure 3: Simple D-Tree and Instances

The algorithm queries all the instances of the first class in the list. Then it queries for the next related instances as specified by the classes in the list. Each path from the start class to the end class represents a separate row in the initial table. Splits occur when there is a one-to-many relationship between classes.

To show an example, consider the D-Tree in Figure 3. When the algorithm runs, it first queries for all instances of A and gets back A1. It then queries for all instances of B that are related to A1 and gets back B1 and B2. At this point there is a branch so it picks one path and puts the other path in a stack to be expanded later. Assuming it expands B1 first, it queries for the instances related to it and gets back C1. It then queries the final related instances which are D1 and D2. The final results for this branch are two paths: A1-B1-C1-D1 and A1-B1-C1-D2. It goes back and explore B2's branches and gets back A1-B2-C1-D1 and A1-B2-C1-D2 for a total of four possible paths and thus four rows in the initial table.

If the algorithm is run on the tree in Figure 4 from the beginning, it gets back A1 and A2. Expanding A1 firsts gets B1 and B2. Expanding B1 first gets C1. To get the related D instance, it looks up what instance of A was in the path so far. It finds that the instance of A was A1 and its related D instance is D1. This gets the path A1-B1-C1-D1 and also A1-B2-C1-D1 once it goes back and expands B2. When it expands A2's path, it gets B2 and C1. To find the related D instance, it goes back to A2 and finds that it is D2. This gets back one path which is A2-B2-C1-D2. Thus there will be three rows in the table.

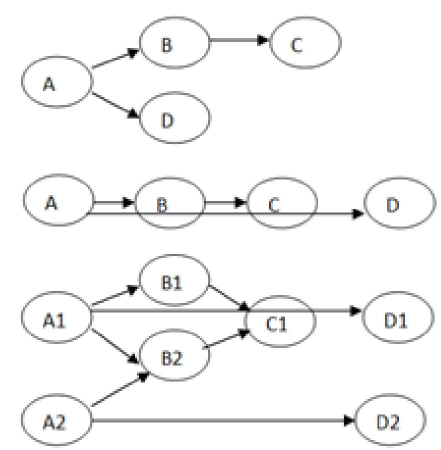


Figure 4: Complex D-Tree, the flattened tree, and Instances

When there are no related instances for a particular node, the algorithm can either stop the expansion and not report that path or report a "not found" instance for that position. It then assumes the next instance related to any "not found" instance is also "not found" which allows it to expand the rest of the path if it is not at the end.

**Constructing view table**

Once a path is found, the system can extract the properties to report. Since each instance at a particular position in the path corresponds to a specific node in the D-Tree, it simply looks at that corresponding node to find what properties are expected to be there and report them in the table. "Not found" instances are assumed to contain no information.

Each property to report has a corresponding target name that the user can specify which is used as the column name in the table. When constructing the table, our system finds the column with this name and places that property's value there. Roll-up properties are handled accordingly.

Once the initial table is constructed, the pivot operation is applied if specified. A map is created that maps each unique value in the column specified as the Row ID to all of its properties and a list of values from the Pivot Column Value for each unique Pivot Column

Name value found. This map is then read out with the Pivot Value Operation applied on the Pivot Column Value lists to create the final table.

## A TOOL TO BUILD AND PRESENT IFC TABULAR VIEW

The i-model makes it easier to build a D-Tree intuitively using a graphical user interface. In this tool, we can select and open an IFC i-model from local disk. The IFC schema is loaded automatically and presented on the left pane shown in Figure 5. D-Tree is built in the Denomalization Pane. Classes are dragged from schema pane and dropped in the proper D-Tree node in the Denomalization Pane. Then the relationship of the edge and properties of the class could be selected below. Roll-up relations can be selected and column name can be set manually.

The tool also provides a section for setting up the Pivot definition as shown in Figure 6. Figure 7 demonstrates the preview pane which shows the result of running the transformation.

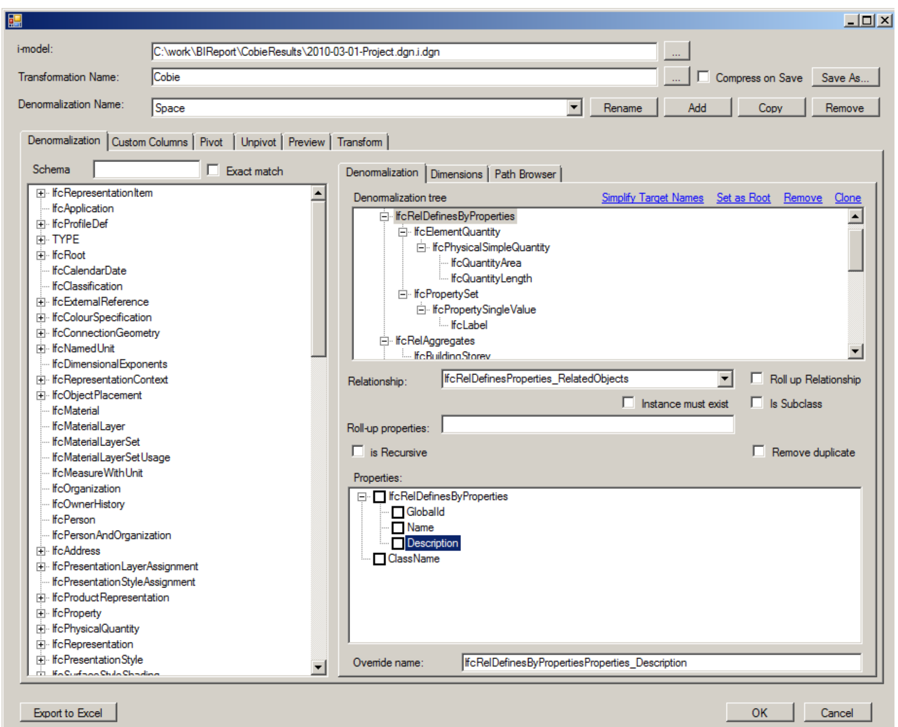


Figure 5: D-Tree definition

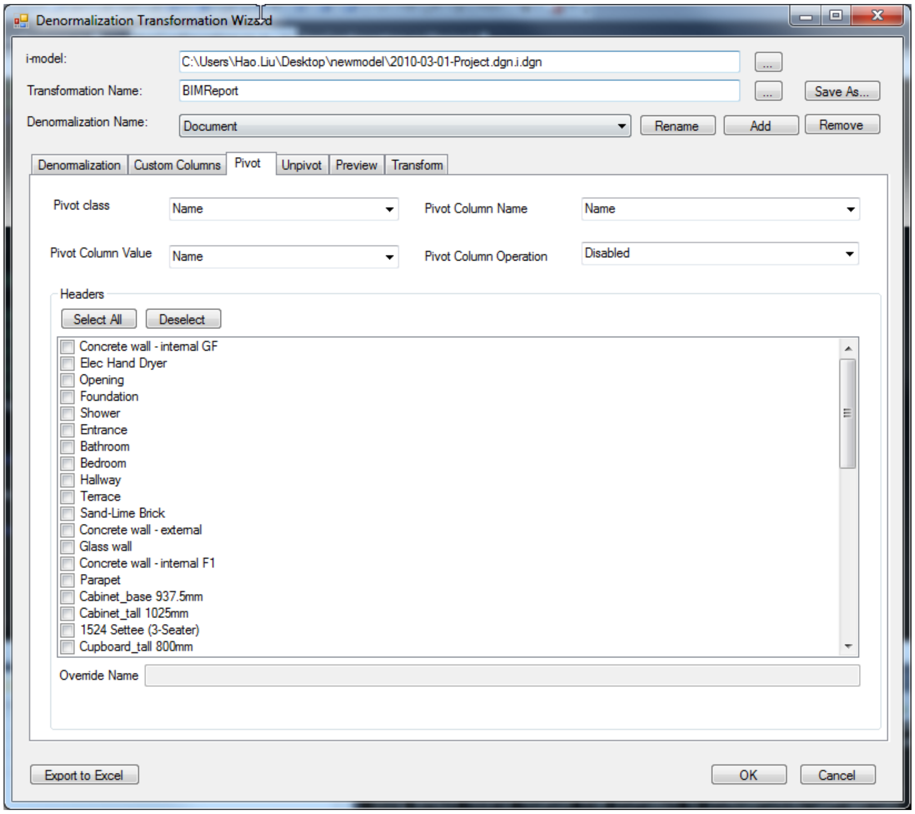


Figure 6: Pivot definition

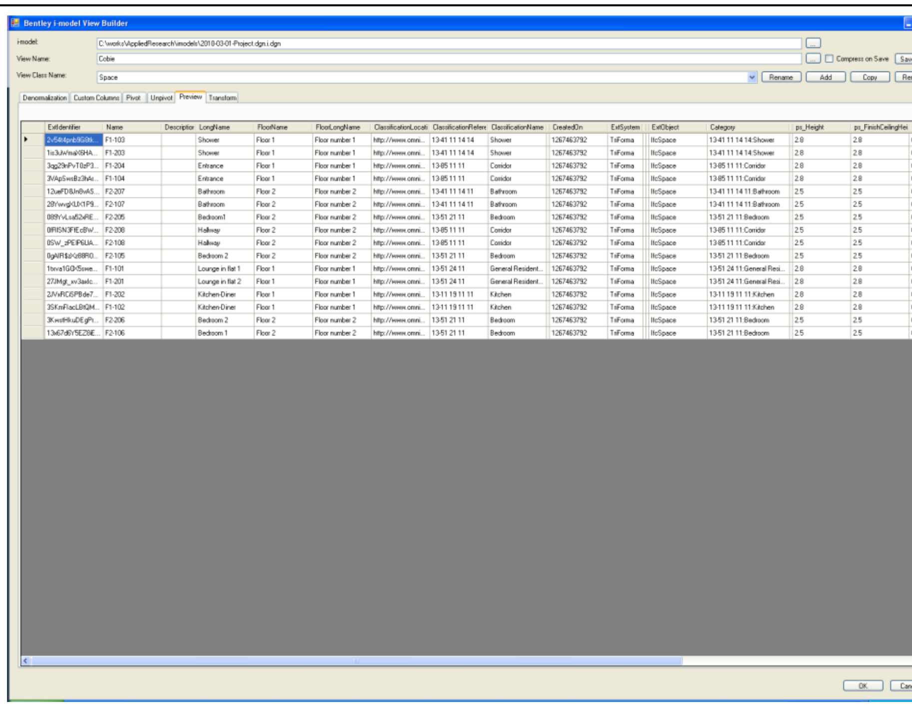

Figure 7: View Table preview

## CASE STUDY – COBIE HANDOVER FROM IFC I-MODEL

Construction Operations Building Information Exchange (COBie) is an internationally recognized data exchange standard and format for BIM project data handover. COBie delivery is an Excel workbook, which is a perfect use case for testing our concept and tools.

Here are the steps in this case study:

1. We get an IFC file in "STEP physical file" format
2. Import it into MicroStation and produce an i-model to get the schema embedded
3. Use our View Builder to create tabular views for Contact, Space, Facility etc, which are required in COBie
4. Query the views through ODBC in Excel

We were able to create tabular views containing information required by design phase COBie. Figure 8 shows an example of defining Floor view.

There were several issues we have to address outside the view definition. One is that COBie has the concept of Asset. It is a filter of rows getting into the view. The current view definition does not support filter logic. We applied the filter after querying all the data back. The other issue is that IFC models created by different software packages may model the BIM data differently. For example, IFC models exported from Revit have Revit specific property sets. The view definition has to change accordingly. Finally, the Attribute page in COBie is a normalized form of properties. We needed a un-pivot operation to generate it.

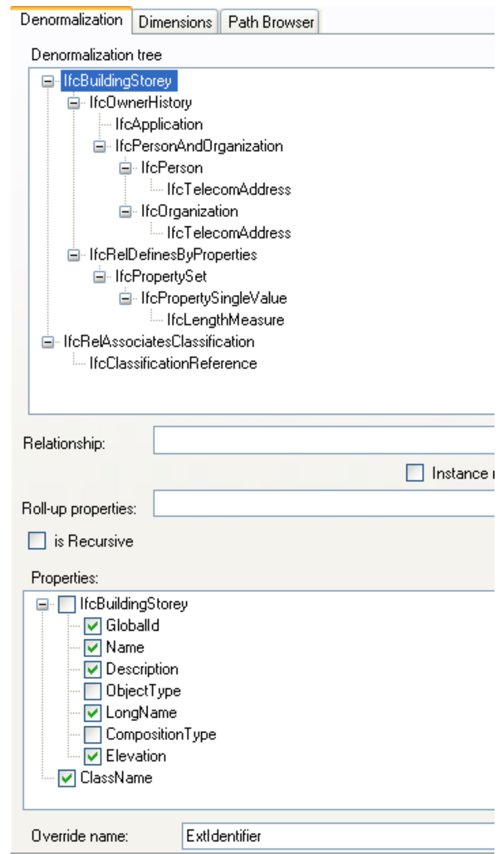


Figure 8: COBie Floor View defination

## CONCLUSION

A method of defining and exposing tabular views of IFC model was presented in this paper. A tool was created to demonstrate this method using i-model which is intended to be industry neutral and freely accessible. Any software can use Bentley's free i-model toolkit including the tool discussed in this paper to create and access i-models. IFC models in native STEP or XML format to participate in downstream workflow in Bentley software are not limited to those created by Bentley software. Given that ODBC is an open industry standard, many enterprise applications can access the defined views natively.

Our research demonstrates that creating tabular view of IFC model is a viable solution for handovers and other downstream consumptions. Exposing the view via ODBC is a cost effective way to extract IFC data in an i-model from other applications. With basic SQL query skills or VBA programming skills, many potential applications in the area of reporting and business intelligence could be built on IFC models.

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# PROCESS MODELING FOCUSING ON BIM AND INTERDISCIPLINARY DESIGN RELATING TO STRUCTURAL PLANNING AND DESIGN

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The Architecture, Engineering, and Construction (AEC) Industry is finding that "silo" barriers promote limitations within the community, as a result inhibiting effective and efficient collaboration even with the advent of new ways of thinking. The current industry, including the structural discipline, is not realizing how everything should fit together as one cohesive entity. Due to the lack of integrated design processes throughout the community, an Integrated Structural Process Model (ISPM) was chosen as a research focus for development. ISPM has the potential to be a tool to educate the community on the critical tasks and information exchanges needed by the structural discipline to provide the best product.

This paper discusses the ongoing development of the ISPM model based on the critical components of the structural discipline and its place within the broader spectrum of the lifecycle process. The resulting ISPM is overarching in nature in that it is not material or systems specific, yet its scope is comprehensive because it encompasses a project from planning through construction with provisions for future expansion into facility management. The broad AEC impact resulting from the ISPM is that it will prescribe what other disciplines need and gives (information) to be conscious of when designing, fabricating, and/or constructing during model and non-model based tasks. This impact helps to promote full collaboration amongst the various AEC teams. Through the ongoing development of this model, industry practitioners with structural focus feel that the identification of major tasks and information exchanges used to create the best resultant product has direct benefit to them for planning to give the owner the best project results.

Keywords: Building Information Modeling, Interdisciplinary, Integrated Design, Structural Design, Process Modeling

## INTRODUCTION

The transition in the design and construction industry from paper based information flows to digital based ones, including the incorporation of complex product data, has both risks and benefits (Eastman et al. 2005, 2011). In relation to BIM, Fox and Heitanen (2007) have stated in their research findings that there are many challenges to the inter-organizational use of Building Information Modeling BIM. Some of these challenges include object customization capabilities, shortcomings of Industry Foundation Classes

(IFC), archival of information, and multiple design perspectives. As BIM technology and procedures evolve, the concerns over the design of new fundamental impacts can play a pivotal role in the manner of design and construction (Faraone et al. 2009). Eastman et al. (2005) states that there are risks involved in abandoning processes that all employees must understand for new technologies which are not well tested and still have inherent "bugs". However, the payoffs in adoption can reduce engineering and design time as well as supporting fabrication, improving quality, and reducing error of the project.

To date, research efforts in the structural BIM field have focused on limited instances by mapping the process for specific framing systems. Additionally, more generic construction, structural, and whole building processes incorporating information flows have been studied, yet are limited in utilizing integrative concepts. Lee et al. (2012) suggests that integrated process models should look at the larger picture in interaction of the systems throughout the lifecycle. The expected goals of this study are twofold. The first is to develop an integrated and innovative lifecycle process which uses the basis of Integrated Project Delivery (IPD) and includes BIM technology with rooms for expansion as new technologies emerge. This process can serve as a guideline for companies to maximize their efforts in order to give the best resulting design. The second is to provide guidance in the sector looking at interoperability of transferring information (meta data from software to software). This paper discusses the ongoing development of first goal.

## BASIS OF THE ISPM

A process model establishes a foundation which defines workflows of related tasks and exchanges of data between one party and one or multiple other parties. The Integrated Structural Process Model (ISPM) in particular focuses on the structural system as a whole and its interaction with the other disciplines. The integration of computational modeling using digital tools provides a path for new technologies to streamline integrated workflows in the ISPM. Currently there are no specific modeling methods at the currently developed levels. Provisions were incorporated for future expansion for Structural Health Monitoring (SHM) applications, different project types (new construction and Renovation) and for the facility management phase.

As mentioned previously, prior studies were limited in their integrated nature and often lacked depth on task workflow. However, previous studies were not discarded as irrelevant. Instead, these studies were used to develop a baseline model in which the industry expert interviews would build off of to generate integrated notions and common points.

### Purpose

The ISPM's purpose, as touched on previously, is twofold. Focusing on the first goal, it is intended to help any player, team, or discipline better comprehend the interactions between the systems which produce boundaries and products that affect the structural system design and construction process. Companies not familiar with integrated (IPD and similar) means can use this document as a guide to help them work through projects that they are required to participate using this process. Similarly, if a company is looking to update its methodology of design and/or construction, this map can be referenced to start the implementation of certain new methods as needed. The tasks within the workflows are generic so that they can be applied to all structural systems (material based). Furthermore, the scope and implementation of varying complexities of computational modeling (BIM and others) will be incorporated into the write-ups to indicate to readers of what is available to conduct a particular task or subset using ISPM.

### Integrated Arrangement

An integrated lifecycle suggests that there is a collection of participants from a multitude of disciplines which contribute to a project at various points in the lifecycle. The primary teams/individuals that take part on any given building project are: the owner, the architect, the discipline specific systems engineers, the contractors and subcontractors, and the suppliers. A discipline concentration was undertaken in the ISPM development. Only the critical tasks to the structural system were modeled. Tasks not traditionally conducted by the structural firm (e.g. site logistics) were incorporated if it had a structural component (only the structural component was included).

At the upper level of the ISPM is the integration level that focuses on the interaction of systems and disciplines with the structure. Here it is easy to see the primary task relationships that occur and information that is needed before the workflow can continue. To keep things simplistic, the structural specific tasks are in one color and the rest are in another (here structural is blue and the rest are cream). Additionally, the personnel conducting each task was not placed in the task box, but instead left black. This was attributed to the potential for the given personnel performing multiple tasks depending on the specific company or contract language.

## INTERGRATED COLLABORATION AND MODELING

BIM and IPD promote the development of a continuous process of evolution, refinement, and integration that redefines boundaries of the design. The results presented in the following sections take these developments and applies them to the design and construction process. For brevity, only planning through system level design is discussed. Integrated collaboration is essential for the best results as it allows for true collaborative idea generation and exchange amongst the team. Each phase, though difficult to represent in a process, has continuous communications with other systems by sharing information and ideas on what is being done and how to proceed. For more detailed and easier to read maps, please refer to Solnosky (2013).

### Planning

The planning phase is the first phase in ISPM lifecycle. Planning centers on the start of a new construction project and looks at the owner's program and wants to which the design and construction team must produce. Then the ISPM proceeds to define major requirements, which leads to a formulation of architectural concept. At the very start of planning is a vital series of gateways that are introduced and asks for the type of project (new or renovation). This configuration is purposely done to allow for the potential of future expansion to the building project.

Examining planning more closely, the first segment focuses on developing the owner's program and objectives, while the team studies and defines the owner's needs and corresponding constraints. This leads to the development of initial requirements and their priorities from diverse perspectives such as spatial, functional and financial. Next is the development of site, schedule, and cost constraints followed by project execution plan development in which all modeling content, submission requirements, and manners of communication need to be decided, as depicted in Figure 1.

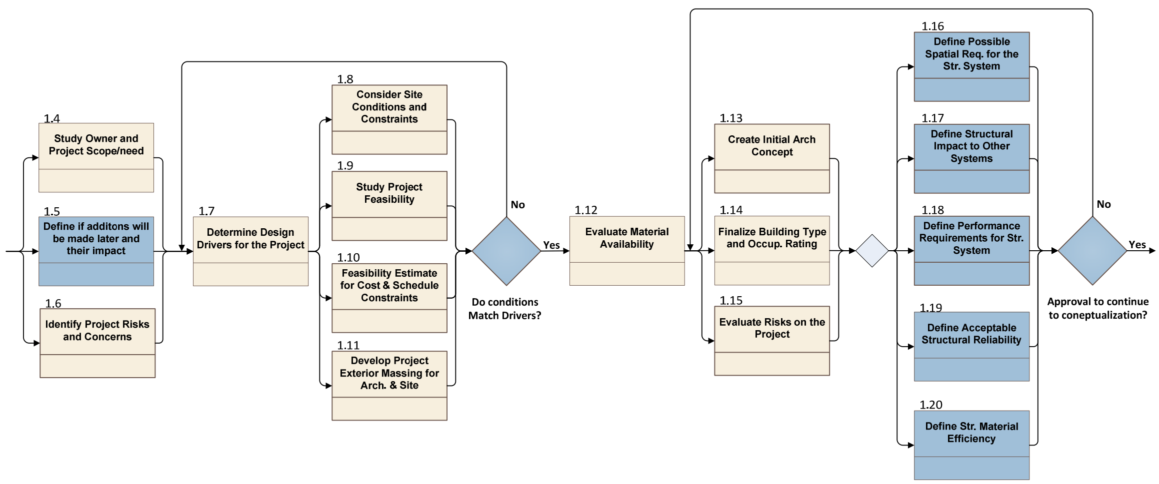


Figure 1. End of the planning phase

The last section is the generation of the architectural concept (note several concepts can be postulated for the next phase to evaluate) while finalizing the building type and initial rating per code. From here, the determination of structural criteria requirements (objectives, spatial impacts, performance, reliability and efficiency) for the designs is decided upon. While it seems abnormal to have the architecture concept before in an integrated delivery, the industry experts felt that some concept needed to be developed in order to have coordination. As such this concept is very broad and open to change with nothing solidified in this early planning stage. It is acknowledged that this is phase is often condensed in practice but emphasis needs to be placed here as this sets the stage for the entire project.

From a computational standpoint, the amount of effort and complexity is minimal at this stage due to the design intent just being understood. From a visual aspect BIM models can provide excellent clear images of what is being postulated. The tasks that can use BIM modeling to advance the task include: site, cost, and schedule constraints, architecture concept, structural spatial requirements, and structural impact. Models here are often discarded and many models may be utilized (one for each concept).

## Conceptualization Design

Conceptualization design can be considered a mixture of planning and pre-schematic design from a traditional delivery perspective. In the conceptualization design, the team has two functions structurally. The first is to develop characteristics and relationships for the structural system, including any prefabrication aspects. The key to prefabrication here is to acquire feedback from specialty subcontractors. This stage looks holistically at the project to determine the best solutions and studies the program for flaws while ensuring the project can be completed within the given constraints. Major prefabrication assemblies are sorted out depending on the complexity requires, thus driving the system selection. Interactive rationalization between the architecture and the structure is conducted, resulting in coordinating any focal point that the structure will serve. Concurrently with this, having early input by building officials will allow for a smoother process, in particular for those with new/unproven systems.

The second is to explore structural alternatives and propose possible solutions that meet the project goals and owner requirements, shown in the center of Figure 2. From here the proposed solutions are then evaluated based on coordinated interaction with other systems. During this period, a fabricator can be brought in early to give input on holistic concepts and determine if the ideas are feasible at the conceptual level or should be scrapped. From a structural perspective, all of the configurations, materials, and subsystems developed are refined and narrowed by the team as a whole to a particular set of configurations and/or material class (moment frames from a configuration or steel for a material). The project drivers, owner requirements, and input from parties are the basis of system narrowing. These selections are then sent to the system level design phase for further narrowing and full system design.

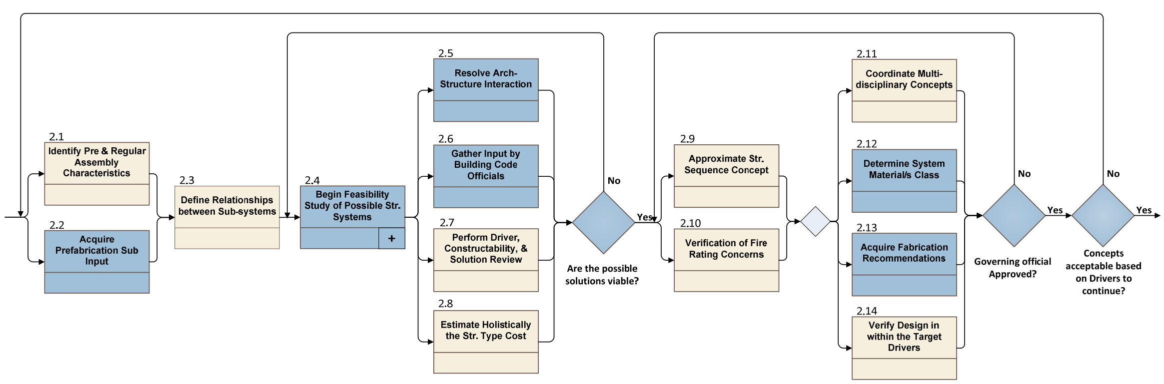


Figure 2. Conceptualization Design Process

Computationally, Conceptualization design is more advanced as now models are not merely a visual tool but also an analytical tool. Visually, BIM models here offer graphical scenarios that can be compared other postulated systems to look for those interactions. Furthermore with constructability, major visible concerns on construction can be spotted in the model to closer inspections later in the lifecycle. Analytically, now structural systems can be based on routines and holistic practices when linking to databases on properties and limitations of different systems. While most of the modeling is still simplistic, architecture-structural interaction can have a significant complexity jump.

This is due to its generative parametric design which uses advanced software to generate many alternatives based on rule sets (Schumacher and Otani 2012). The tasks that can use BIM modeling to advance the project are: prefabrication assembly characteristics, feasibility study of Possible Structural systems, arch-structure interaction architecture concept, structural spatial requirements, and structural impact.

## System Level Design

System level design is where the gravity, lateral and foundation systems concept options are condensed and refined through iterations with narrowing points until final solutions emerge that have been fully designed at a system member detail level. When looking back to traditional delivery methods, system level redefines traditional Schematic Design (SD), Design Development (DD), and Construction Documents (CD) phases by decision points into a single flowing phase. In the ISPM, the system level design phase is composed of three sections of which are schematically represented in Figures 3 and 4.

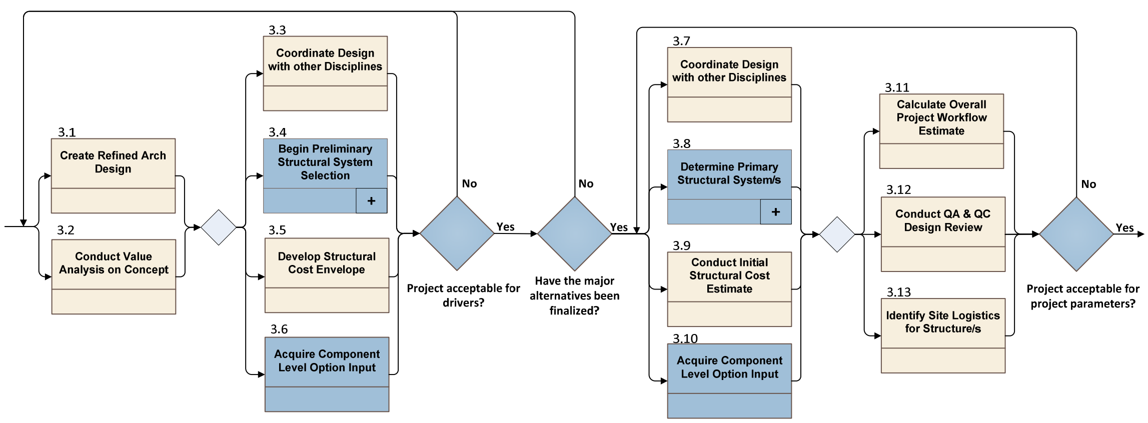


Figure 3. System Level Design Process (Section 1)

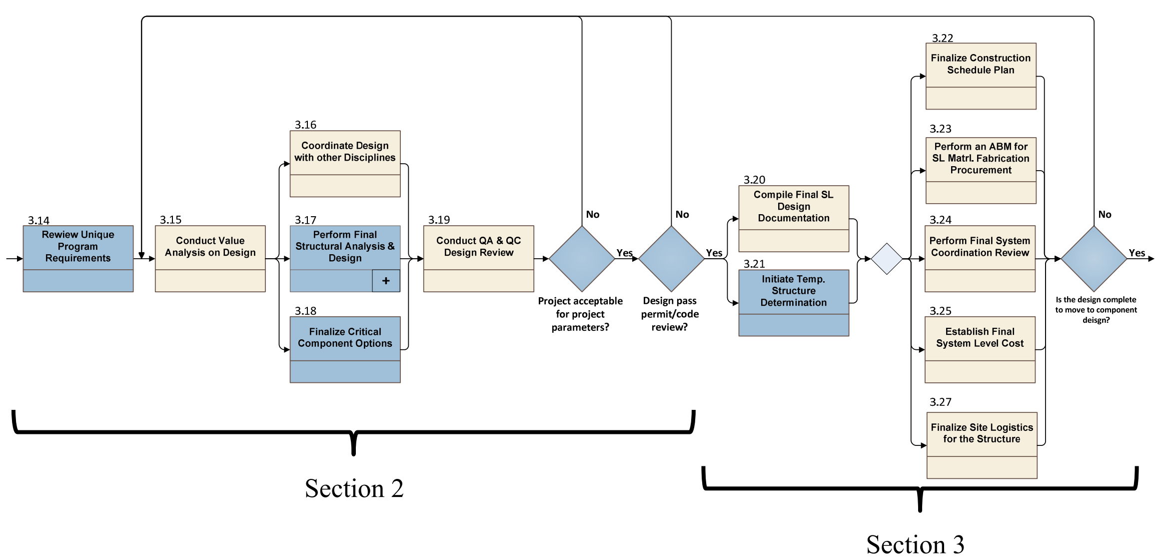


Figure 4. System Level Design Process (Section 2 and 3)

The first section (Figure 3) is essentially the narrowing of the configuration concepts down into the final system type, depicted in Figure 3. During this section, the structural concepts from conceptualization along with further refinement of the structure are sent to other disciplines that heavily influence their designs. These include cladding, skylights, wall and floor MEP penetrations, and stairs which lead to more integrated coordination throughout this stage with more component level consolation input. Early site logistics, schedule production, and estimate of design improvements can start in the latter half of the first section. During this phase, structural configurations are generated in a variety of different orientations then through iterations the best are selected. Selected designs are progressed to a second selection phase which uses more accurate data in regards to interactions, behaviors and loadings to narrow the system down to the best selection.

Section two (Figure 4) focuses on the advanced analysis, design and optimization of the structural system after a unique requirement check and a value analysis has been performed on the designs to date. The value analysis results in refinement suggestions for value improvement of the first section designs. These results are incorporated based on team agreement. From here, the structural system is finalized through advanced computational methods of analysis and design. Moreover, component level options in critical coordination and behavior regions are decided upon. A quality control and assurance review is then performed on both the designs and the models; these can be internal or external to a company/project team. To finish section two, a code and permit review is conducted to ensure designs meet expectations.

System level design, section three (Figure 4), starts off with the compilation of the final design authoring models which will allow for the downstream tasks to be conducted. Concurrently, the initial temporary supporting structure can be selected and narrowed in options which will be design in the component level design phase. The remaining section is the finalization of site logistics, system level cost, construction schedule for the structure, a formal coordination review, and an Advanced Bill of Materials (ABM) for structural procurement.

Computational work, especially around BIM in system level design, takes on a variety of uses and complexities in model content and usage. Here the level of development can range from a L200 to L400 depending on the system and its material composition. It was recommended by the experts interviewed that if this process is embraced the extra modeling detail here can make for smoother processes. Advanced computational efforts in structural design are often used to get the best efficiency. It is recommended at this stage to model the metadata as the models are developed and ensure this data is accurate. The tasks that can use BIM modeling to advance the project are vast and many, the main classes are: structural system analysis, design and design communication, coordination reviews, site logistics, estimating, material takeoffs, and scheduling.

## Computational Modeling

The trends in computer modeling encompassing the structural domain go hand in hand with the tasks as we move into a BIM focus process. The majority of work is done to some extent computationally with varying levels of complexity depending on the phase. Six primary categories were formulated based on function during the ISPM development:

1. Design authoring modeling
2. Analysis and design modeling
3. Coordination modeling
4. Code compliance modeling
5. Fabrication modeling
6. Construction and planning modeling

Historically speaking, over the last 20 years the structural profession has often relied heavily on the generation of sophisticated analytical and design models to describe the systems (Cai 2006, Jacobi 2007). While there are advanced capabilities available, the modeler needs to know when to properly use such capabilities to avoid having to discard the model later on if such advanced capabilities are used prematurely. Because of this, modeling complexity increases as the project continues, but can have complexity spikes early in the lifecycle depending on the structural type. To counter large models, structural engineers have often traditionally compartmentalize the models for easier manipulation and faster computation time, despite the advent of BIM.

It was agreed upon by the vast majority of the interviews conducted that a complete understanding of the tool, methods, and possibly most important, sound engineering judgment is needed to obtain accurate and reliable results. A combination of these can make the difference in reducing severe errors and provide savings in time and effort. Without the background knowledge, the application of these methods from simple to complex projects can have pitfalls. Furthermore, it was suggested that to achieve the best resulting performance of the structural system, the best possible modeling techniques are necessary and should always be strived. Currently, the validation of the appropriate techniques used for each task and the complexity level is being conducted.

# INDUSTRY BENEFITS & FUTURE WORK

This paper describes the development of an integrated structural process model that examines the relationships between structural discipline and other disciplines/systems. The work proposed is still ideal in nature, in that is has not yet been validated against actual projects at the time of publication. Upon completion of the validation, the ISPM will be able to provide guidance on how to design structural systems in an integrative environment, producing the best results for the owner and project utilizing new modeling concepts and techniques. Beyond this study, future work could include the integration of facility management, the development of the renovation process, and the integration of structural health monitoring system design, construction, and implementation.

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# CAPTURING AS-BUILT INFORMATION FOR A BIM ENVIRONMENT USING 3D LASER SCANNER: A PROCESS MODEL

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**ABSTRACT**
Building Information Models (BIM) are becoming a new design standard for storing and exchanging information about a facility. Usually, as-built information is available for new buildings whereas existing buildings, rarely, have a 3D as-built BIM model. 3D Laser Scanners offer the opportunity for faster and less error-prone creation of as-built BIM models compared with the traditional methods of surveying. The process, from scanning a facility until an as-built BIM model is created, is not fully automated yet. Several attempts towards that problem (Scan-toBIM problem) have been identified in the literature review. However most of them propose systems that are case based and cannot perform under different conditions. The need for a general description of a system upon all the stakeholders can work on, discuss and provide solutions emerges: process models were found to correspond to that need. This paper surveys how a Scan-to-BIM system can be modelled. To that end, the IDEF0 modelling methodology has been employed and the Scan-to BIM Process Model has been created. According to the generated Process Model, a general description of the Scan-to-BIM process has been given and relevant problems and areas of discussion have been identified. Finally, implementation and validation of the model are proposed for future work.

**KEYWORDS**: As-built information, BIM, IDEF0 modelling technique, Process Model, 3D Laser Scanner

## INTRODUCTION

According to the Government's New Construction Strategy of 31 May 2011, UK Government decided that by 2016, building proposals are required to be fully collaborative BIM with all project and asset information, documentation and data in an electronic format (Cabinet Office, 2011).Besides the use of BIM for better collaboration, many authors mention that one of the major advantages of using BIM is that the generated BIM model can be used as a source of as-built information (Lordc and Dawood, 2009; Woo, et al., 2010; Klein, et al., 2012). In particular, as-built information becomes very important, especially in a digital format, as facility managers or owners can

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use it for: space and equipment management (Bansal, 2011), retrofitting and renovation (Woo, et al., 2010), awareness and control of building energy consumption (Lordc & Dawood, 2009), determination of building's object location etc.

One popular surveying method for capturing as built information is the 3D Laser Scanning. 3D Laser Scanner is a technology that captures as-built information in a more accurate and fast way. Until an accurate as-built BIM model is obtained an intense and error-prone procedure is followed, requiring excellent user's skills. Many recognize that the automation of this process could bring benefits to the Architecture, Engineering and Construction / Facility Management (AEC/FM) industry. (Brilakis, et al., 2010)

Several authors throughout the literature review try to tackle the Scan-to-BIM problem and propose systems that they capture and transform as-built information suitable for a BIM environment in a more automated way. However most of these attempts are domain based or employ certain software and therefore their results cannot be applied under different conditions or generalized. As Brilakis et. al (2010) mention the automatic generation of BIM is a multidisciplinary problem (Brilakis, et al., 2010). The description of the Scan-to-BIM process without being domain dependent, can help in related problems to be addressed better, provide general guidelines and create a neutral model upon solutions are given. General description of systems can be given using Process Models.

The above mentioned ideas have been the main drivers of this project. Thus, our aim has been to model the Scan-to-BIM system. Our attempt aims to create a Process Model of the Scan-to-BIM system that can be used to describe the system's function, inputs, outputs, mechanisms and controls and based on that to identify possible areas of discussion. A Scan-to-BIM Process Model is a starting point for improvements and changes in the Scan-to BIM system/problem.

## LITERATURE REVIEW

The current state of the Scan-to-BIM procedure can be described as: the spatial information of a facility is scanned and raw point clouds are created. Additional supportive devices like cameras and RFIDs capture facility's semantic information like material, price etc. The raw point clouds are registered in a common coordinate system and a unique point cloud is obtained. The registered point cloud is segmented and geometry is attached on surfaces or volumes. Finally semantic information is attached, objects' attributes and objects' relationships are established and a BIM model of the scanned facility is created.

In current practice, the above described process is very intense, error prone and time-consuming (Brilakis, et al., 2010). It is widely accepted that Scan-to-BIM process would benefit from automation. Several attempts towards this direction have been identified in the literature review (Seokbae, et al., 2002; Cerrada, et al., 2007; Arayici, 2008; Brilakis, et al., 2010; Krukowski and Arsenijevic, 2010; Tang, et al., 2010; Klein, et al., 2012).

These try to tackle the problem of the Scan-to-BIM automation, however, being case based and domain restricted. Though the nature of the problem is complex and concerns the automation of an inter-domain system, a holistic approach of the Scan-to-BIM system is needed.

Holistic approaches require models that describe exactly what a system does, what controls it, what means it uses to perform its functions and what it produces in terms of input, output, and interrelated functions. A model provides a description of the functions and their interfaces that must be captured and understood in order to translate systems requirements into solution neutral specifications.

Eventually the generated process model can be used to define systems requirements, to analyse system needs or system functions, to design the system or to become the reference-model for continuous improvement. Thus, the development of models that describe a system can result beneficial for the development and improvement of the systems (Rahmouni and Lakhoua, 2011).

Further implications of process models concern the following: if the model is used systematically it can perform system analysis. Furthermore the developed model can be used to check the integration of new parts on the modelled the system. Improvements on the system can be done having the model as a tester. Finally by modelling a system, analysts, designers and managers can communicate easier having a common comprehensive language. (Benard et al. 2008).

## THE SCAN-TO-BIM PROCESS MODEL

### Development and Representation of the Model

Several modelling techniques have been reviewed and the IDEF modelling methodology was found to be suitable for our project. The development and representation of the Scan-to-BIM Process Model was accomplished according to the IDEF guidelines described in IDEF (1993).

The development of a Process Model requires the definition of the model's perspective, purpose and view point. Particularly, purpose of the model was to describe the Scan to BIM system, independently of certain domain or software. Additionally, as user's can perceive and deal better with problems related to systems when these systems are conceptually modelled the user's point of view was the chosen one. The developed conceptual models can be easier understood, analysed and therefore can assist to the problem-solving procedure. Finally the model has been developed from a functional perspective because its scope is to represent the Scan-to-BIM system in terms of interrelated functions and data flow.

After perspective, purpose and point of view are defined, the model is depicted using 1) graphic diagrams, which are top-down diagrams representing a basic function that is decomposed in its sub-functions (parent diagrams are decomposed into child diagrams) 2) text, which provides supporting information for a function and its purpose and 3) glossary, where all the used acronyms used in the modeling are defined. Diagrams, text and glossary should be cross-referenced to each other so as process models to be precise. All of these should meet the rules of syntax and semantics as defined in (IDEF, 1993)

**Description of the Model**

The Process Model starts with the Top-Level diagram as seen in the diagram below (Figure 1). The Top-Level diagram gives the boundaries and the overall idea of the system. Also are depicted the purpose and viewpoint of the model. The Top-level diagram is labelled as A-0 and named as "SCAN-TO-BIM". The main input, output, control and mechanisms elements relevant to the "Scan-to BIM" major process also are illustrated. The input of this function is the spatial and semantic information of a scanned "Facility" and the output is the as-built "BIM model" of the scanned facility. The major controllers of this function are the "Project's Requirements" (C1) and the already "Available knowledge" (C2) e.g. old CAD drawings or libraries of primitives that help to CAD object recognition. The mechanisms involved in this process are the "3D Laser Scanner" (M1), other "Supportive Devices" (M2) like cameras and "Algorithms and Methods" deployed during each step of the process.

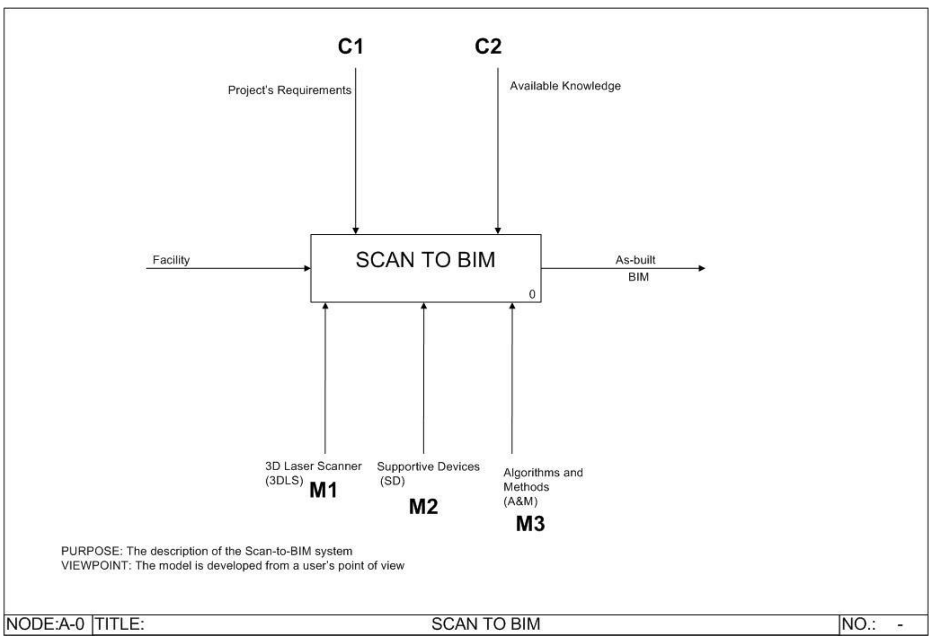


Figure 1: Top Level Context Diagram

After the Top Level Diagram is created, the Process Model is further described with the following 4 diagrams: the context diagram named as "Scan-to-BIM" (A0) which is decomposed into the "Scan Facility" (A1) diagram, the "Pre-Process Point Clouds" (A2) diagram and the "Create as-built BIM" (A3) diagram (see figure 2). The acronyms, keywords and terms that have been used in the diagrams are defined in the glossary given in the next table (Table 1).

Table 1: Glossary of the Scan-To-BIM Model

| Term | Meaning |
|---|---|
| 3D Laser Scanner | Device used to capture 3D spatial information generating point clouds |
| Algorithms and Methods | Algorithms and Methods employed during a Scan-to BIM process with certain role in each step |
| As-built BIM | A facility's BIM model , describing exactly how the facility was constructed |
| Available Knowledge | Already existing CAD plans of the scanned facility |
| Supportive Devices | Additional to 3D Laser Scanner equipment to capture semantic information like colours, material and price |
| Facility | A scanned object, building, entity etc. |
| Facility's Semantic Information | The semantic information of the scanned facility, like colours, material and price. |
| Facility's Shape Representation | The geometrical shape of the scanned facility |
| Facility's Spatial Information | The spatial information of a scanned facility in terms of point clouds |
| Project Requirements | Statements that describe the general requirements in the project. |
| Registered Spatial Information | The gathered spatial information obtains a common coordinate system applying registration algorithms. |
| Triangulated Spatial Information | Spatial information where triangulation algorithms have been applied (the result is a triangular mesh) |

The context diagram "SCAN-TO-BIM" (A0) describes the Scan-to-BIM process. The "Scan-to-BIM" (A0) process occurs when spatial information is captured with the use of 3D Laser Scanners and is converted into a semantically rich BIM model. At the last stage of "Create as-built BIM", BIM models are generated. Its decomposition is described below:

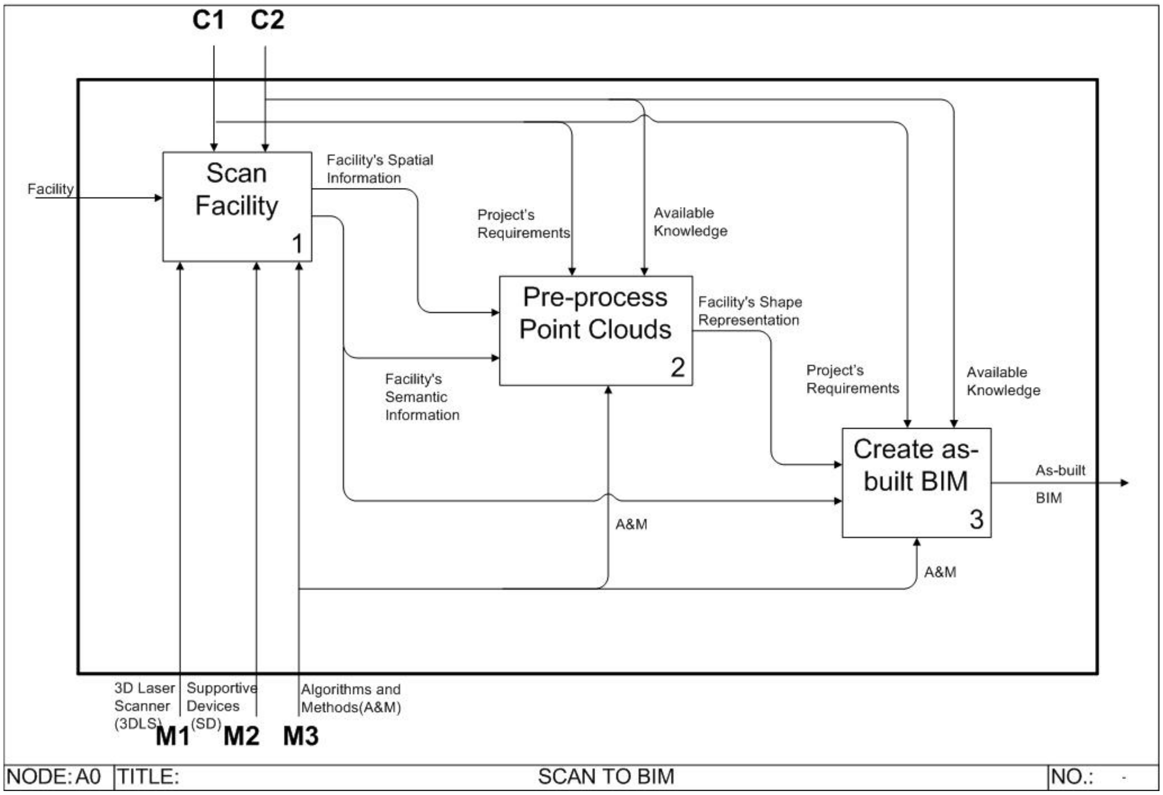


Figure 2: The A0 Context Diagram is decomposed in three sub steps.

**"Scan Facility" (A1).** The "Scan Facility" sub-process includes all the functions needed in order to acquire spatial and semantic information of the scanned facility. In this step, the input is the scanned "Facility" and the outputs are the "Facility's Spatial Information" and the "Facility's Semantic Information". Mechanisms used in this function are "3D Laser Scanner" (M1), other "Supportive Devices" (M2) like digital cameras that captures additional information like colour and certain "Algorithms and Methods" (M3) used by the software of the Scanner. As single scans cannot capture all objects' dimensions, more than one scans are required to capture all the 3D spatial information. The number of scans depends on the accuracy needed and the requirements of the project. Therefore, one control element is the "Project's Requirements" (C1). "Available Knowledge" (C3) has been considered also as control. The decomposition of the "Scan Facility" sub-process is not demonstrated here due to limitations of space.

**"Pre-process Point Clouds" (A2).** "Pre-process Point Clouds" (A2) activity (Figure 3) comes from the Box 2 of the A0 diagram (Figure 2). In this phase, the raw point clouds under the name "Facility's Spatial Information" have to be converted in a format suitable for object recognition. The "Process Point Clouds" function is decomposed, as it is seen in Figure 3, in three activities: "Register Raw Point Clouds", "Apply Triangulation" and "Apply Segmentation". These activities may occur simultaneously or in a random order. It is assumed that these functions occur with the order "Register Raw Point Clouds", "Apply Triangulation" and finally "Apply Segmentation" so as the diagrams to be more comprehensive, clear and in a logical order.

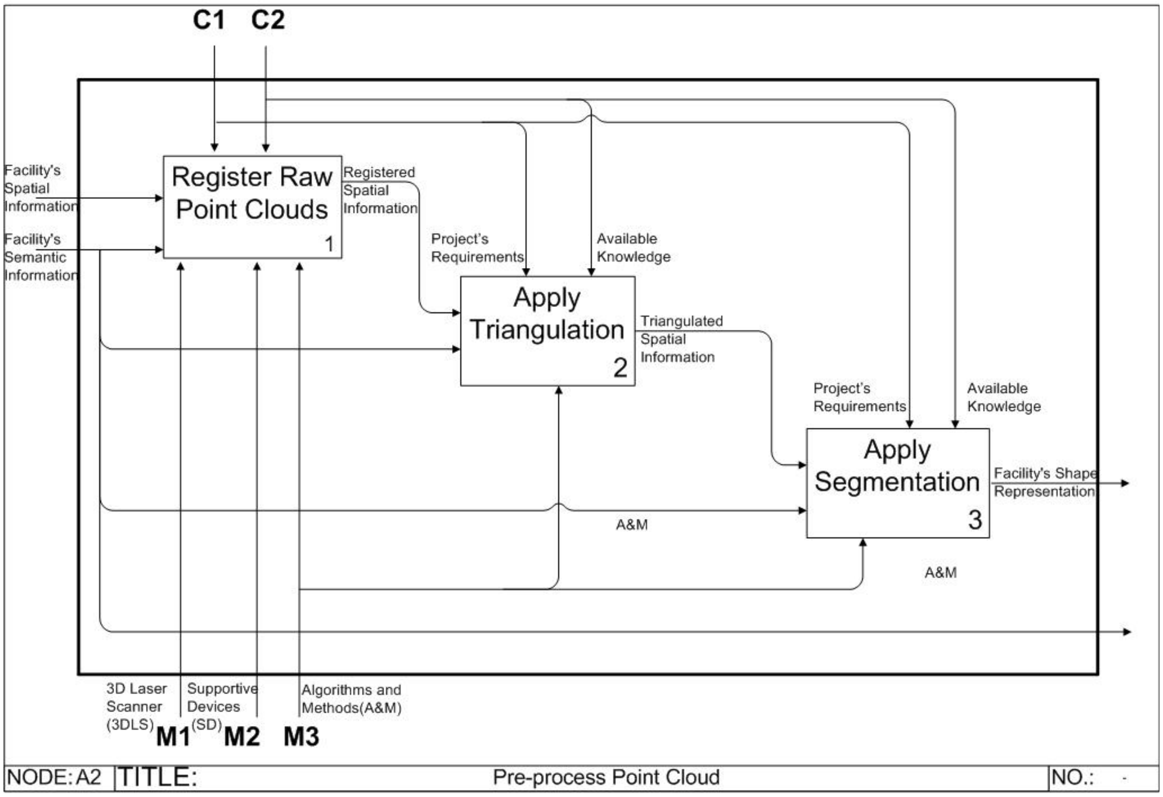


Figure 3: The decomposition of the "Pre-process Point Cloud" activity.

"Register Clouds": In this function the "Facility's Spatial Information" (input) which has the shape of raw point clouds is converted into a single registered point cloud. Thus the output is the "Registered Point Cloud". The mechanism involved is the "Algorithms and Methods" (M3) (e.g. iterative closest point algorithm (ICP) algorithm and its variants) is applied (GSA, 2009). "Project's Requirements" (C1) and "Available Knowledge" (C2) are the controllers of the sub-process.

"Apply Triangulation": In this activity the generated point cloud is converted in a triangular mesh. Therefore the "Facility's Semantic Information" and the "Registered Spatial Information" (inputs) are applied "Algorithms and Methods" (M3) controlled by the "Project's Requirements" (C1) and "Available Knowledge" (C2) in order to produce "Triangulated Spatial Information" (output).

"Apply Segmentation": In this stage, the input of the previous activity is used in order to obtain the "Facility's Shape Representation". The latter is the input of the "Model as-built BIM" (A3) diagram.

**Model as-built BIM" (A3).** The activity "Model as-built BIM" (A3) is a decomposition of box 3 in the A0 diagram (Figure 2). This activity can be further decomposed into the activities "Detect Geometry", "Classify Objects" and "Establish Relationships". After these three sub-processes are accomplished, the final as-built BIM model is obtained. The decomposed activities are not further discussed since paper's space is limited.

## DISCUSSION

**Implementation of the model**

The above described Process Model of the Scan-to-BIM procedure has illustrated the main functions, inputs, outputs, mechanisms and controls involved in each activity that affect the result in a Scan-to-BIM process. The main input of the process is the data gathered using 3D Laser Scanners and other supportive devices. The obtained data flows from one level to the next ones. At the end both semantic and spatial data is used to generate an as-built BIM model of the scanned facility. As the nature of semantic and spatial data is different the problem of data format emerges. The establishment of general accepted data format standard emerges. Currently, the IFC standard offers a great opportunity.

Another relevant problem of the system is related with the used mechanisms. In the Process model have been depicted algorithms and methods that are used in each activity. Although different kinds of "Algorithms and Methods" are employed in each step (registration, triangulation, segmentation algorithms etc.), there are some attributes that should be considered before an algorithm is designed or applied. Some of them concern the level of automation, the computational complexity and the extensibility of the algorithm. The problem of how to design an algorithm with these attributes and that can process data of uneven nature is also of a great importance.

Finally the main controllers of the system which are "Project's Requirements" (C1) and "Available Knowledge" (C2) though that can affect the final BIM mode, ways to be integrated in the model should be found. Quantifiable measures could help at this point.

Summarizing the related problem of the system, concern three main areas of discussion:

- the format of the data
- the design and development of algorithms that they can support dynamic and heterogeneous data
- the integration of project's requirements and prior knowledge.

**Likely Benefits of the model**

The developed model can offer benefits to stakeholders and other participants of the Scan-to-BIM system. In particular, the Process Model being sector independent can become a common vocabulary and therefore can improve the communication between the involved members of the Scan to BIM system. As our attempt has led us to identify some problems of the system, similarly the model can be used by software developers, users, hardware technicians, engineers to identify further problems and factors that affect the accomplishment of different tasks inside the Scan-to-BIM system. The related persons to the system can also understand how their activities may influence the system. Finally, the model can be used to more easily define the key decisions on a system the used algorithms of the specification of projects' requirements.

**Limitations of the model**

Limitations of the model have identified and listed as:

- The model has not been validated yet. Possible validation of the model concerns interviews with stakeholders.
- It has not depicted the information flow. This aspect is of a main importance, especially in terms of the information that it flows and the file format that is needed. Especially in the case of the "Scan-to- BIM" system these problems are becoming more important due to the nature of the highly semantic BIM models.
- The model does not give the dynamic aspect of it, which means that this aspect of time is not depicted. Most of the functions are presented to occur in a sequence order. Models that could give the aspect of time are IEDF2 dynamic diagrams.

## CONCLUSION

BIM and as-build BIM become popular in the AEC/FM industry. The as-built information can be captured deploying the technology of 3D Laser Scanning providing results in a fast way. Due to the fact that the Scan-to-BIM process requires several users' input and high skills, much research aims to tackle the problem of how to automate that procedure. Many of them have successful results but only for certain cases or they are domain restricted. The need for an overall approach emerges.

Process models, being sector-independent, provide the opportunity for an overall description of a system upon all the stakeholders can work on and discuss and provide solution having a common comprehensive language. This project has presented our first attempt towards the creation of a general Scan-to-BIM Process Model. The IDEF0 technique has been chosen as the modelling method and a Process Model has been created. According to the generated Scan-to-BIM Process Model, there have been identified certain areas of discussion and related problems. These are summarized as: data format, algorithms, and predefined values.

Limitations of time did not permit the validation and application of the model. Future work could fill these gaps. Also, future work concerns the creation of dynamic related model and information flow.

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# A LIBRARY OF STANDARDIZED MODEL COMPONENTS FOR RETAIL PLUG LOADS

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## ABSTRACT

Miscellaneous electric loads comprise a growing percentage of commercial building energy use, expected to increase from 31% to 43% of total commercial building primary energy use by 2030. In building energy simulations, these loads are often poorly modelled or are outright neglected. A big box retail building with grocery was found to contain over 700 MELs. Through this study, 256 of those devices were metered. That time-series data informed the creation of 260 EnergyPlus model components. Those model components were made publicly available through the newly developed Building Component Library (BCL). The use of these BCL components was worked into a modeller workflow, resulting in accuracy equal to the best of the commonly used plug load modelling strategies for an example building. Detail and repeatability were improved.
Keywords: building component library; miscellaneous electric loads; plug loads;

## INTRODUCTION

Miscellaneous electrical loads (MELs) are the building end-use category that represents all energy other than that consumed by traditional end-uses (HVAC, lighting, water heating). That includes plug loads as well as hard-wired devices like elevators and sliding doors. MELs make up 30% of the energy use of commercial buildings (McKenney, et al. 2010). According to the Energy Information Agency, MELs are the fastest growing building end-use (2011). As the traditional end-uses have become more efficient and use of consumer electronics has increased, the percentage of building energy consumed by MELs has significantly increased (Nordman and Marla 2006).

Relative to the traditional building loads, MELs are not well studied. Lack of available power and use schedule data for a number of prevalent devices lead TIAX LLC to recommend that the Department of Energy (DOE) conduct power measurements for a sample of MELs in key building types. Researchers at a number of DOE National Laboratories also noted the lack of measured data for MELs in their report concerning the development of the Commercial Reference Building Models (Deru, et al. 2011). Six of the fourteen building types merely use engineering judgment as their data source for plug and process load intensity.

In building energy simulations, these loads are often poorly modelled or are outright neglected, given that there are few standards regulating the building modelling field. Therefore, modellers adhere to their own best practices for how to approach the modelling of building elements such as plug loads. For the aforementioned Reference Buildings, data from several sources was combined to create MELs load intensity values for each zone activity type. The values listed in Appendix A of that document serve as MELs input values for many energy modellers. A 2008 methodology for building energy modelling published by researchers at the National Renewable Energy Laboratory (NREL) included a table of plug and process load intensities by building type (Griffith, et al. 2008). The data for that table came from the California Commercial End-Use Survey. The Commercial Buildings Energy Consumption Survey (CBECS) is a national study that includes a breakdown of commercial energy by end-use (Energy Information Administration 2003). CBECS miscellaneous load energy intensities are sometimes used as input values for building energy simulations.

This variety of acceptable methodologies creates inconsistency in the building simulation field regarding the modelling of MELs. In reviewing 270 projects, Turner and Frankel (2008) found that not only was there a wide range of modelled plug load values (as a percentage of total energy use), but that more than half of those projects did not include any miscellaneous loads at all, a grave omission given their growing importance. The amount of variability in the modelling of MELs leads to variability in accuracy of predicted energy use. In a number of studies comparing model predicted energy use to actual energy use, the authors cited underestimation of plug loads as one of the top reasons for erroneous predictions (Torcellini, et al. 2006, Norford, et al. 1994, Demanuele, et al. 2010).

The objective of the work presented in this article is to investigate the possibility of using model components derived from measured data for the plug loads in a whole building energy model. This strategy is then compared to commonly used methods.

## METERING OF PLUG LOADS IN A RETAIL BUILDING

### Building Description

In general, the area of MELs research is focused on office equipment. MELs in retail environments are largely understudied. This is particularly concerning since 60% of the energy in food retail buildings is consumed by MELs. A building that contains both food and non-food retail areas was desired to cover a wide range of retail environments. When choosing a representative building for a MELs study, the building shell and HVAC system were not important. The key characteristic of the ideal building is a wide distribution of space types and therefore a statistically sound representation of plug loads. Nationwide, 75% of all miscellaneous energy use is consumed in buildings over 4,645 $m^2$ (McKenney, et al. 2010). This research demanded a large building incorporating many of the most common building types. The store selected to be metered is a 20,290 $m^2$ big box retailer with grocery. It is operated 24-hours a day. The store contains a bakery, deli, produce section, pharmacy, vision centre, bank, hair and nail salons, photo centre, and fast food restaurant. A thorough inventory of the MELs in the store revealed more than 700 plug load devices. Those devices represent 308 individual product models. Cash register equipment is an example of a plug load type containing multiples of the same device.

**Metering Process**

An effort was made to meter as many of the device models as possible within the time and budget constraints of the project (Frank, et al. 2011a). For devices with multiple instances in the store, dependence on user interaction was determined through metering of each a "more frequent", "average", and "less frequent" use case. The measurement equipment was a plug-through style meter. Therefore, only the plug loads and not the hardwired MELs could be metered. Privacy and security concerns precluded any equipment in the bank, pharmacy, and security room from being studied. Additional plug loads were physically inaccessible (unreachably high, behind immovable objects, or inside cabinets). Twist lock plugs were accommodated through plug adapters, but non-standard plug types and 240V and 480V devices could not be measured due to meter limitations.

Time series data was recorded for power, voltage, current, energy consumption, and power factor at a 30-second sample rate. Numerous criteria caused a meter with on-board data storage to be chosen, and a 30-second sample rate seemed to produce a good balance between sufficiently fine granularity to study devices with rapid transient load behaviour and a long enough duration before reaching data storage capacity. Each device was metered for a total of four weeks, and then the meter was rotated to another plug load.

**Metering Study Length**

Ideally, a study of plug load energy consumption on a per-device basis would be conducted over an entire year so that seasonal fluctuations could be recorded in addition to diurnal and day-of-week dependencies. Nine months was allotted for this study and fifty meters were deployed throughout the store. The sampling period for each device had to be short enough that the meters could be rotated amongst the hundreds of pieces of equipment in the building. Four weeks is long enough to establish diurnal patterns and tease out day-of-week dependencies. The 20 devices that showed a propensity for seasonal variations were metered for five to nine months.

Plug loads with refrigeration elements were thought to have a dependence on zone temperature. Eleven such devices were metered concurrently with localized temperature measurements. Throughout the duration of the study, 256 plug loads were metered. Of that, 165 were unique device models, more than half of the unique models in the building. The 20 devices metered for an extended period of time included duplicates of the same device with different use patterns and plug loads predicted to have increased energy use during times of increased store occupancy. The meter user manual indicated a decrease in current and power factor accuracy below 60 W. The other variables maintain their high level of accuracy at low power. Due to 61% of the plug loads having at least one operating mode below 60 W, no analyses using power factor or current could be used.

## PLUG LOAD MODEL COMPONENT CREATION

The time series data collected for hundreds of plug loads served to inform energy model components for incorporation into whole building simulations. A desired outcome of this project was that in addition to the process described in this publication, the model components themselves would be available to the building modelling community. All of the components described in this paper are available in a web-based database recently released by NREL, the Building Component Library (BCL) (Long, et al. 2011).

### Energy Simulation Platform

The OpenStudio tool suite for EnergyPlus is being extended to work with the BCL. Currently, OpenStudio forward translators can convert information stored in EnergyPlus input data files (IDFs) for use in the OpenStudio environment (National Renewable Energy Laboratory 2010). An additional tool under development for OpenStudio is planned to include the capacity for a local user library of BCL components. With this pending collaboration in mind, all components in this project were designed to be compatible with OpenStudio. While these model components bear the extension .idf, they are not complete, executable files. They are components that help the user build a whole building model from the ground up. Each component consists of an equipment object and corresponding schedule.

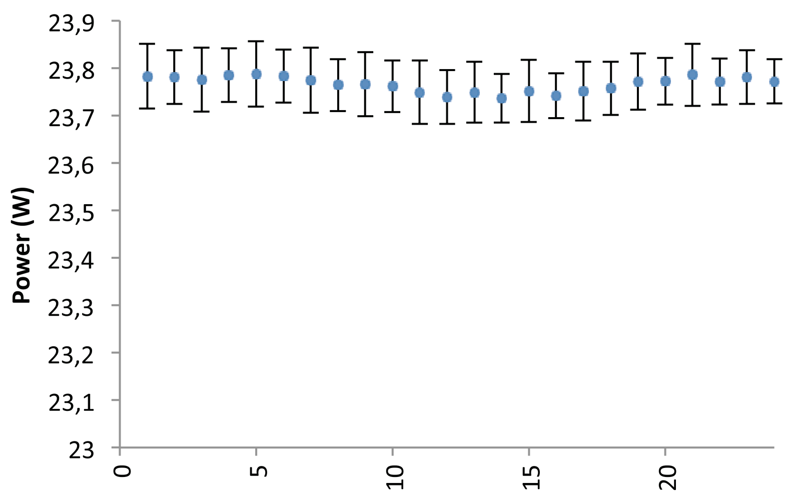
### Creating component schedules from time series data

The operating modes of each device were extracted through the clustering technique described in Frank, et al. (2011b). Then, the operating mode for each hour was used to produce schedules for each component. Unlike EnergyPlus, OpenStudio only has the capacity for compact schedule objects, so all components adhere to the Schedule:Compact organization.

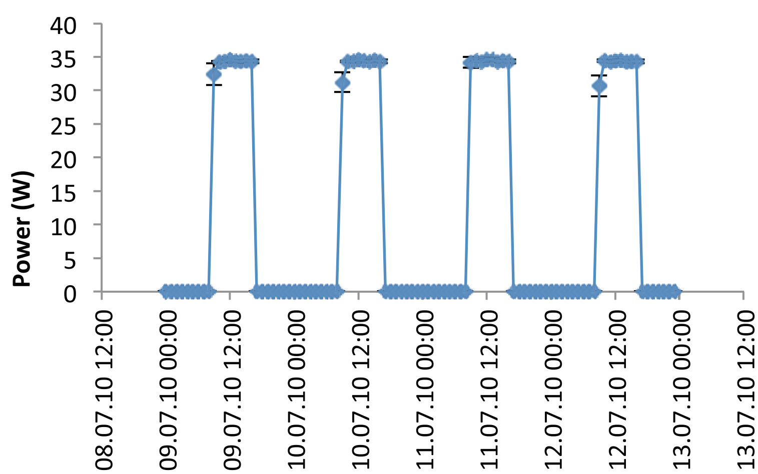
In the case of multiple instances of the same device metered independently, each step of the component standardization was conducted separately. Once the multiple instances were found to be consistent, the datasets were averaged together to produce a single model component. Multiple instances subjected to different use patterns (i.e., cash registers used with different frequency) were intended to be modelled as different use cases – high, medium, low. The analysis revealed that the spike in power level resulting from user interaction was too brief to affect the hourly energy use. Therefore, only one model component was created from these multiple energy profiles.

The first step in converting the measured data into standardized schedules was averaging the 30-second data into hourly pieces. Hourly power levels were plotted across the four-week time period for a visual inspection of the data. When a visual inspection and the mode extraction signalled a constant device, no further analysis was needed and the component was modelled with a schedule of 1.0 for all hours of the year. Each week was considered individually to examine for day-typing. This behaviour is common in office equipment where the usage on an unoccupied Sunday differs from a workday. None of the plug loads in the retail setting showed this behaviour. This is likely due to the store operating daily without any unoccupied days. None of the component schedules have a day-of-week distinction; the schedule is applicable for AllDays.

Once each device was found to lack any day-type dependence, all the days in the dataset were averaged into one 24-hour profile. This profile was converted to a fractional schedule. Figure 1 shows this 24-hour profile for three devices (1b shows it repeating over a four day timespan) with bars marking the standard deviation of the measurements. Fifty-five per cent of the plug loads studied showed time-of-day dependence. Those that did not were either devices with refrigeration elements or were constant loads such as modems or safes. The distinction between devices exhibiting time-of-day dependence and those that did not is visible in Figure 2.




a)

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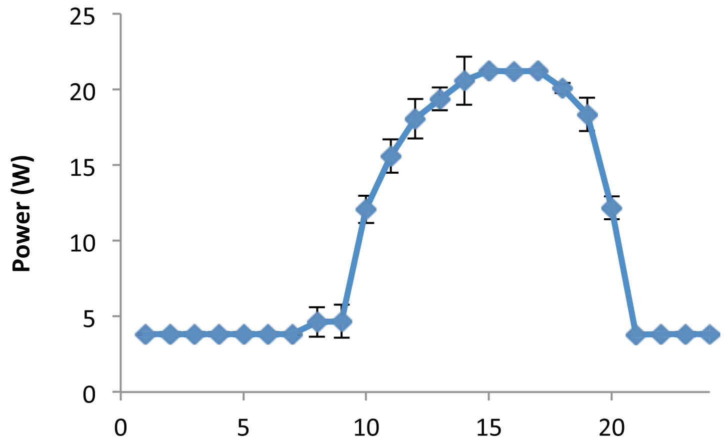
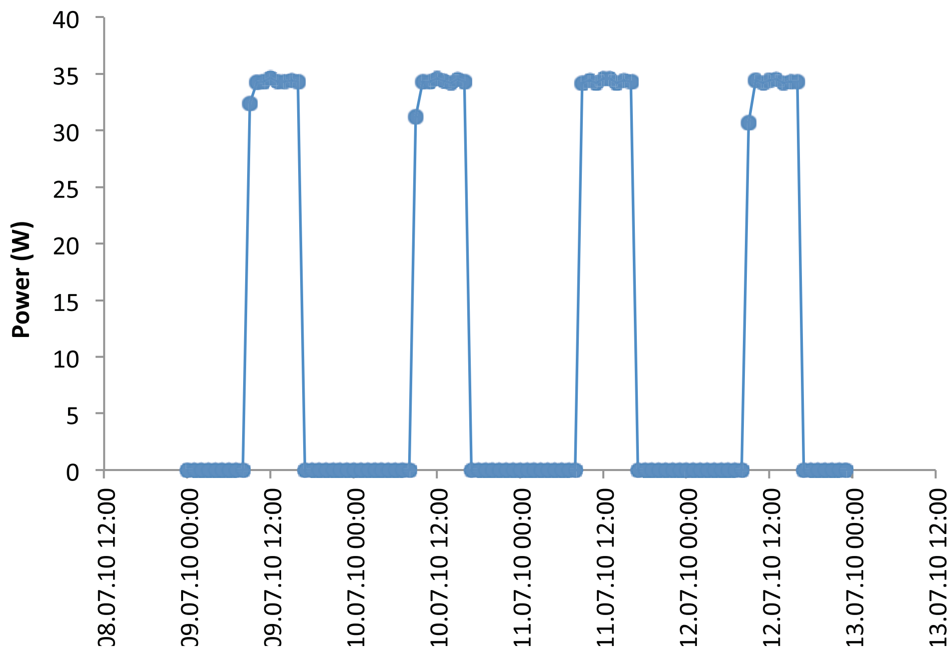
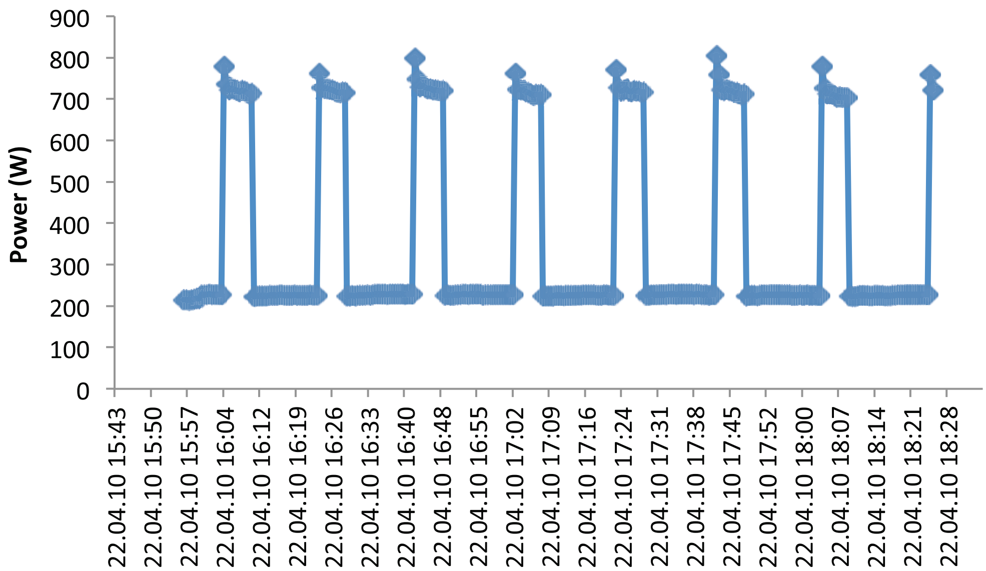



c)

Figure 1. An average profile with error bars indicating the standard deviation of the hourly values for a) an average daily profile of a constant device, b) four days of an on/off device, and c) an average daily profile for a continuously variable device.




a)



b)

Figure 2. An average profile for a) a device with time-of-day dependence, and b) a refrigerator device exhibiting no time-of-day dependence.

All model schedules have some form of hourly schedule. None of the plug loads in this study necessitated a distinct week-level schedule. Few devices showed any potential for seasonal variation. Similarly to the high, medium, low use case example, the duration of increased power mode due to occupant usage was too short to impact the average hourly energy consumed for all 20 devices subjected to extended metering.

Refrigerators, freezers, and soda vending machines have time-of-day independent compression cycles. The length of that cycle varied per device from eight minutes to six hours. The sub-hourly cycles were averaged out over the hour. For the devices with longer cycles, the cycle was represented in the hourly schedule. The comparison of the energy use with localized temperature showed no statistical evidence to support a relationship between zone temperature and power consumption of these devices within the temperature range found in typical building spaces.

The majority of devices exhibited constant power behaviour. Electronics on display in the 24-hour store are good examples of constant loads. If there was less than 5% difference between the maximum and minimum recorded power levels, the device was modelled as a constant load. In this building, the vision centre, fast food restaurant, nail and hair salons, bakery, and deli were not operated 24-hours a day. Devices in these spaces are indicative of on/off or on/standby devices. Such plug loads have a binary occupancy dependence: they are on when the store is open and off/standby when the store is closed. The EnergyPlus Runtime Language (Erl) allows for variable interdependence (i.e., plug load schedule as a function of zone occupancy) to be coded into a model. At the time of this writing, however, OpenStudio does not support Erl objects. Therefore, binary occupancy-dependent devices are modelled as two components – in a 24-hour setting and a 10am-9pm setting. Plug loads with continuous occupancy dependence (energy use as a function of the number of occupants in a zone) were modelled as static schedules based on typical operation. Forty-five per cent of devices showed a binary occupancy dependence and 28% showed a continuous occupancy dependence, making this an area for component improvement. Ultimately, the metering of plug loads in a single retail store provided data for 260 model components.

## COMPARISON OF COMPONENTS TO COMMON PLUG LOAD MODELLING METHODS

The big box retail building used for this study has been submetered for the last five years. Each of the traditional end-uses as well as the miscellaneous loads were recorded in 15-minute time steps. Like the data recorded for the individual plug loads, no distinct seasonal trends could be seen in the miscellaneous load at an aggregate level. The researchers responsible for the submetering of the building estimated that on average 276 MWh/year are consumed by the type of miscellaneous plug loads examined in this project. The remainder of the miscellaneous load is due to MELs such as hard-wired sliding doors and security equipment.

The building component strategy predicted an annual energy use of 221 MWh/year. Much of the difference between the predicted and actual energy use is likely due to the off-limits areas of the store that could not be inventoried or metered. An energy consultant involved in minimizing the energy used by plug loads would mostly likely have access to that information, improving his or her model accuracy.

Figure 4 shows the annual energy consumption of the most common plug load modelling strategies in comparison to the component method and the actual building end-use. Only the upper end of the reference building range accurately predicted the annual energy use of the plug loads. The component-filled model was marginally more accurate than the traditional reference building model. The component method, however, leaves less room for variability among modellers. Each piece of miscellaneous equipment is accounted for, rather than basing the total plug load energy on the size of a zone. This gives the component method a level of precision that the other methods do not have.

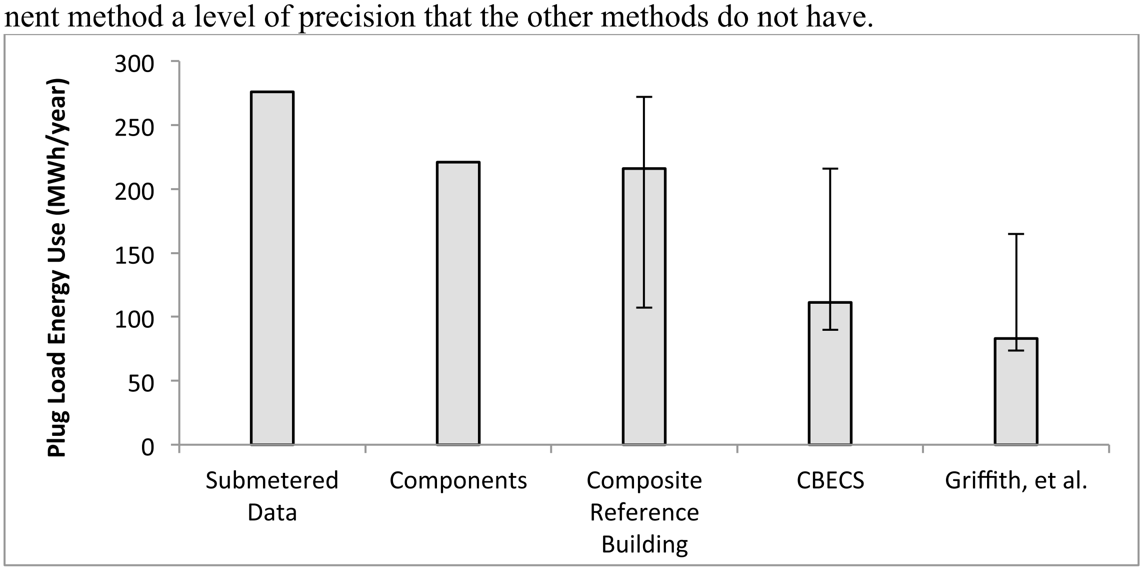


Figure 4. Annual energy consumption of plug loads for a building, compared to the values predicted by the component modelling strategy and three alternative methods.

The expected outcome of this project was that the BCL components would increase the model quality through both improved accuracy and improved detail. The accuracy shown is on par with the best available strategies, but the improvement in model detail is the largest contribution to the modelling field. A plug load EUI for a zone lacks information about what devices are located in that zone. Beyond recording extensive notes in the text input file for a program, there is no way for this information to be passed on to collaborators through the model. Components from the BCL clearly retain device type, manufacturer, and model information with the component. With the ability to cite individual components, there is also a tangible record of all of the attributes and assumed occupancy conditions that pertains to the device. That greatly reduces the amount of modeller-generated documentation that needs to accompany the plug load portion of a whole building energy model.

Reducing energy from plug loads is achieved through proper selection of devices and training of the building occupants. The improvement due to a more efficient television, for example, can be demonstrated with the straightforward substitution of that component in a model. A modeller wishing to demonstrate that same reduction in energy using a zone EUI would have to recalculate that value and thoroughly document that procedure.

## CONCLUSIONS

In a collaborative study, 256 plug loads were metered in a big box retail and grocery store. This research focused on using time series energy consumption data to inform the creation of EnergyPlus model components. These components encapsulate the behaviour of each specific device (maximum power, operating schedule, etc. – in a length of EnergyPlus code that can be added to any whole building model. The components have been made available to the public through NREL's Building Component Library. Their inclusion in that library makes them independently citable through a URL, which allows for a novel approach to modelling plug loads. Currently, the most common method of modelling plug loads is through a $W/m^2$ approximation. A library of model components allows for a process in which each device in the building is separately accounted for. Such a procedure provides the following benefits over a $W/m^2$ approach: it accounts for the actual devices using energy in a store rather that approximating per floor area, the citability makes model reproducibility easier, and linking the energy performance to the object's metadata (manufacturer, model, etc.) enables details about the device to stay with the energy model. The component method of MELs modelling was demonstrated to have accuracy consistent with the most commonly applied $W/m^2$ approximations for one example building, while improving model detail and repeatability.

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# Development of Desiccant and Evaporative Cooling based 100% Outdoor Air System

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## Abstract

The purpose of this paper was to introduce and investigate the energy and thermal performance of a desiccant and evaporative cooling based 100% outdoor air system. The concept of proposed system is decoupled system with dividing the sensible and latent cooling load in order to restrict the usage of vapor compression cooling system. In this point of view, sensible cooling load of process air is treated by indirect and direct evaporative cooler and latent cooling load is eliminated by liquid desiccant system. Control strategies and energy saving potentials of proposed system was also modeled and estimated using the TRNSYS 16 energy simulation program. It was assumed that 7500m$^2$ office room is served by proposed system. The annual performance of proposed system was simulated.
As a result, the energy reduction effect of 87~89% was shown in the heating season compared to conventional VAV system. Energy reduction of 49~53% and 53~63% was shown in the intermediate and cooling seasons, respectively. It was conclude that the proposed system can be saved 74~77% of annual total operating energy with respect to the conventional VAV system.

Keywords: Evaporative cooling, Liquid desiccant, 100% outdoor air system

## 1. Introduction

In order to respond to global warming and climate change, globally many countries have made every effort to reduce greenhouse gas emission through Tokyo Protocol and adoption of Bali Roadmap since UN framework convention on climate change in Lau, Brazil in 1992 as the starting point. Accordingly, since building sector accounts for 25~50% of entire energy consumption in most of the countries, it is thought to need to have urgent efforts to reduce greenhouse gas emission now.
As a method to solve this problem, eco-friendly evaporative cooling based 100 % outdoor air system using evaporative latent heat of water has been developed through previous studies (Kim et al. 2011, Kim et al. 2012) and high-energy performance was compared with that of existing vapor compression refrigerant based air conditioning system and verified through simulation and empirical research.
It was found that energy consumption of 80~90% was reduced compared to conventional

VAV system in winter and intermediate season. Nonetheless, it was somewhat hard to obtain energy saving of 50 ~ 60% annually. In addition, in case of Korea where it was hot and humid in the summer, it was found that it should consist of system including substances with high ODP (Ozone depletion potential) such as cooling coil in order to maintain the high quality indoor environment.

If dehumidification system is applied to IDECOAS system developed on previous studies as a method to solve this problem, temperature and humidity is maintained at the proper level without conventional cooling coil operation. This desiccant system can also lead to develop the eco-friendly evaporative cooling based 100 % outdoor air system and maintain comfortable indoor environment.

Both solid and liquid desiccant systems could be used in this dehumidification system. However, a variety of studies showed that a liquid desiccant system absorbed more moisture in the air compared to a solid desiccant system and could save more regeneration energy because the temperature required for regeneration was lower (ASHRAE, 1997; Katejanekarn and Chirarattananon, 2009). It has been also known that liquid desiccant system has advantage to reduce the fan energy due to lower pressure drop in the air side of the dehumidification part (Lowenstein, 1998; Narayanan, et al, 2011).

Until now, a variety of theoretical and experimental studies about a liquid desiccant system have been conducted (Babakhani and Soleymani, 2009; Burns et al, 1985; Chen et al, 2006; Fumo and Goswami, 2002; Gommed and Grossman, 2007; Jain et al, 2011; Ren et al, 2007; Thornbloom and Nimmo, 1995; Yin and Zhang, 2008). However, there are not many studies on control methods and annual operation energy performance through application of office building and implementation of liquid into evaporative cooling systems.

This study investigated components of improved desiccant and evaporative cooling based 100% outdoor air system and proposed the annual operation method. Through this study, energy performance of the proposed system was investigated and compared with conventional VAV system. This analysis was conducted using TRNSYS 16 which was a commercial dynamic simulation program.

## 2. Desiccant and evaporative cooling based 100% outdoor air system

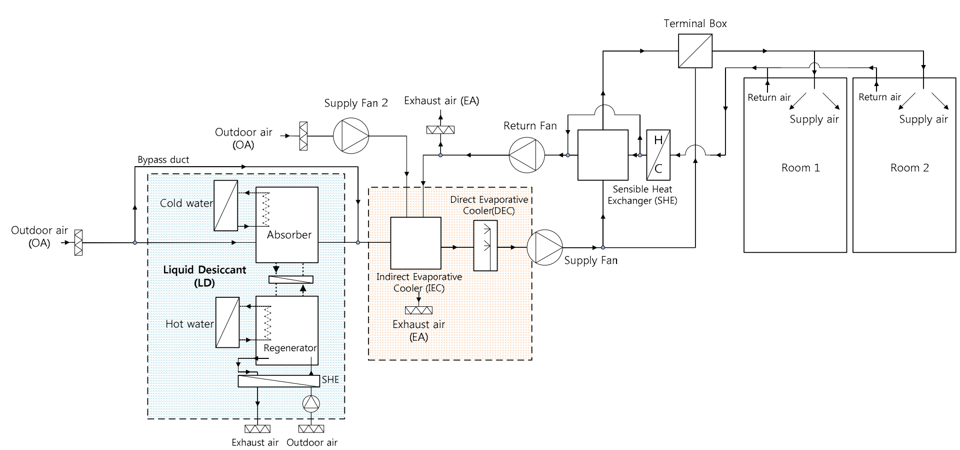


Figure 1. Desiccant and evaporative cooling based 100% outdoor air system

### 2.1 Desiccant and evaporative cooling based 100% outdoor air system

This system, as shown in Figure 1, consists of sensible heat exchanger (SHE), liquid desiccant (LD), indirect evaporative cooler (IEC) and direct evaporative cooler (DEC) in side of supply air. Only 100% outdoor air is used in the same as conventional IDECOAS system and supply air flow rate is controlled depending on the space load variation as the VAV system. Dual-duct or multi-zone system can be also applied.

### 2.2 System operation modes

In the cooling season, introduced outdoor air to cool the space as required is dehumidified by passing through the liquid desiccant system. This processed air is sensibly cooled down while passing through the IEC. This air can be desirable supply air condition by passing through the DEC.

Liquid desiccant is largely divided into the dehumidification part to dehumidify the introduced air and the regeneration part to regenerate desiccant solution that holds moisture through dehumidification. In order to achieve higher cooling effect in the IEC, exhaust air can be supplied into the secondary side of the IEC.

Since the outdoor air is relatively dried in the intermediate season, condition for supply air can be satisfied through operation of IEC and DEC without operation of desiccant. It can be also obtained by supplying relatively more dried air between outdoor and exhaust air to secondary air side of the IEC.

In the winter season, a liquid desiccant system is not operated. Sensible heat between supply air and exhaust air is recovered by operation of IEC and SHE. This operation can minimize the raising space-heating load caused by supply air ventilation. In order to operation of IEC as a sensible heat exchanger, water is not be sprayed to the direct evaporative cooling pad of the IEC.

## 3. Mode of operation

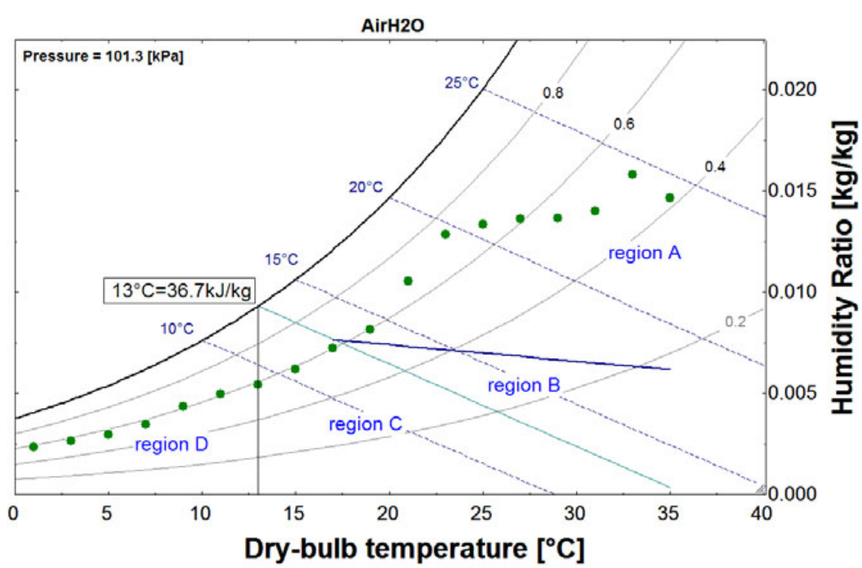


Figure 2. Four regions on the Psychrometrics

The operation modes of the proposed system can be more effectively understood on the Psychrometrics. As shown in Figure 2, the Psychrometrics are divided into four regions (i.e. Regions A, B, C, and D) depending on the outdoor air condition. In each region, the system follows a specific mode out of four different modes of operation.

### 3.1 Operation mode 1

Region A refers to the climate condition in which the outdoor air dry bulb temperature is higher than 13C and the humidity ratio is more than specific value. This value is varied depending on the effectiveness of the IEC and DEC. In this region, the LD leaving air humidity ratio is reached at the specific value in order to reduce and optimize the LD system load. In order to minimize the system load of the LD, leaving supply air temperature is similarly maintained at the entering temperature. And then the IEC and DEC leaving in series, supply air temperature is maintained at 13C (i.e. cold deck setpoint). The IEC and DEC operates at maximum effectiveness in order to maintain the supply air temperature. In order to enhance the cooling effect of the IEC, the scavenger air passing through the secondary channel is selected as the air which has a lower wet bulb temperature between outdoor air and exhaust air.

### 3.2 Operation mode 2

Region B refers to the case in which absolute humidity of the outdoor air is less than specific value and its enthalpy is more than 36.7kJ/kg. By operation of IEC, supply air is modulated to reach 36.7kJ/kg of enthalpy. Then, the DEC performs the maximum cooling until the supply air temperature reaches 13C.

### 3.3 Operation mode 3

Region C refers to the case in which the outdoor air temperature is higher than 13C and the enthalpy is less than 36.7kJ/kg. In this region, the outdoor air can be cooled to 13C by operation of DEC. In this Region, if supply air does not require maintaining the indoor air humidity, the supply air is only cooled by DEC operation without operating the IEC and LD. On the other hand, if maintaining the indoor humidity is necessary, supply air could be pre-heated to reach 36.7kJ/kg of enthalpy by dry operation of IEC as sensible heat exchanger to return air, then the air is cooled and humidified to 13C of dew point temperature by DEC.

### 3.4 Operation mode 4

Region D on the Psychrometrics refers to the case when the outdoor air temperature is less than 13C. The sensible heat is recovered from the exhaust air stream through the SHE in order to keep the neutral deck air temperature around 20C, the neutral temperature setpoint. On the other hand, since the IEC works as a sensible heat exchanger when the secondary channel runs dry, the primary air passing the IEC is heated to 13C by the sensible heat recovered from the exhaust air stream. If sensible heat is not enough to keep supply air temperature setpoints, the heating coil should be operated.

# 4. Energy simulation

## 4.1 Simulation model

The model building was an office building with a floor area of 7500 $m^2$ and 800 occupants. Each occupant was assumed to have a personal computer and do light work according to ISO-7730; the sensible heat was 75 W/person, and the latent heat was 75 W/person. The light density was 13 $W/m^2$. The office building was regularly used from 7 AM to 10 PM for 5 days a week. The heat transfer coefficient (i.e., U-value) of the exterior wall was assumed to be 0.511 $W/m^2C$, and that of the roof was assumed to be 0.316 $W/m^2C$. The window-to-wall ratio was 0.25. In order to estimate the annual performance, the operating energy consumptions of the proposed system, IDECOAS, and conventional VAV system were evaluated. For simulation, the effectiveness of IEC, DEC, and SHE were assumed as 80, 95, and 70%, respectively. These models were simulated using TMY2 weather data for Seoul, South Korea. In this simulation it was assumed that 45% of LiCl is used to solution of liquid desiccant system. The liquid desiccant system operation was analyzed using EES program which holds data about physical properties of liquid desiccant solution. In addition, the simulation for solar water heating system used RET screen. Annual energy simulation based on entire system operation features was carried out using TRNSYS 16 which was commercial software.

## 4.2 VAV-air side economizer system

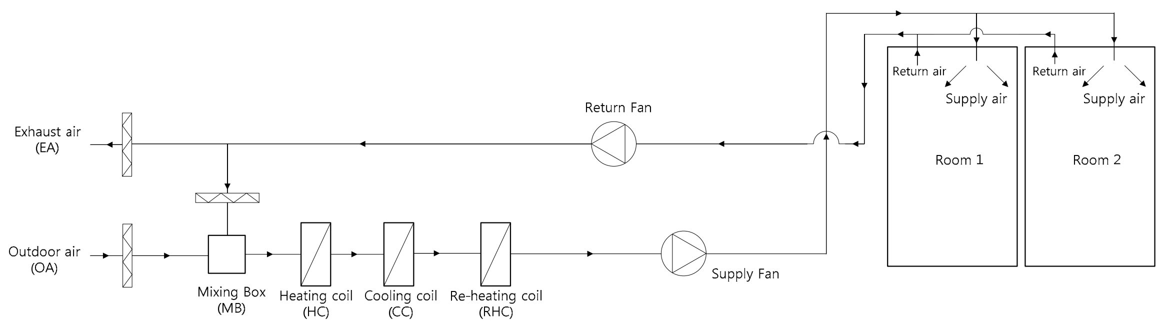


Figure 3. Conventional VAV system configuration

***Mixing box:*** In the cooling and intermediate seasons, cooling load of introduced outdoor air is reduced through mixture of exhaust and outdoor air to maintain proper supply air temperature and humidity. The amount of mixture of outdoor and return air is modulated by control of dampers (i.e. outdoor air (OA), return air (RA), and exhaust air (EA) damper) and operated as the following two cases.

- Case 1: When supply air flow rate is modulated depending on the space cooling load, OA, EA and RA damper is modulated to meet required minimum ventilation rates all the time.
- Case 2: When supply air flow rate is modulated depending on the space cooling load, dampers are fixed to maintain the ratio of RA and OA at 8:2 all the time regardless of required ventilation rates.

In the intermediate season, in order to restrict the increase of the cooling coil load by mixing the outdoor and return air, return damper is 100% closed as a enthalpy based air-side economizer operation.

***Cooling coil (CC):*** Supply air which passes through mixing box is cool and dehumidified at target supply air temperature in CC to maintain the indoor temperature and humidity. In this simulation, it is assumed that CC is modulated to maintain the supply air at 13C. In the CC, energy being used in chiller itself and pump energy to supply the refrigerant to the chiller are used. It is assumed that water cooled chiller is used for this simulation. In case of water cooled chiller, fan and pump energy is consumed in cooling tower.

***Heating coil (HC):*** If the temperature of outdoor air is below 13C, it is modulated to heat it up to 20C not to increase space-heating load by ventilation.

***Re-heating coil (RHC):*** When space cooling load is small in the intermediate or cooling season, RHC is operated to meet the supply air at 14~20C based on the space cooling load. This operation can avoid space over-cooling and maintain space humidity level while the minimum amount of ventilation is introduced.

***Fan (main):*** Fan is modulated to change air volume of supply air based on indoor load. If there are indoor occupants, it is modulated to maintain the proper indoor minimum amount of ventilation.

### 4.3 LD-IDECOAS system operation

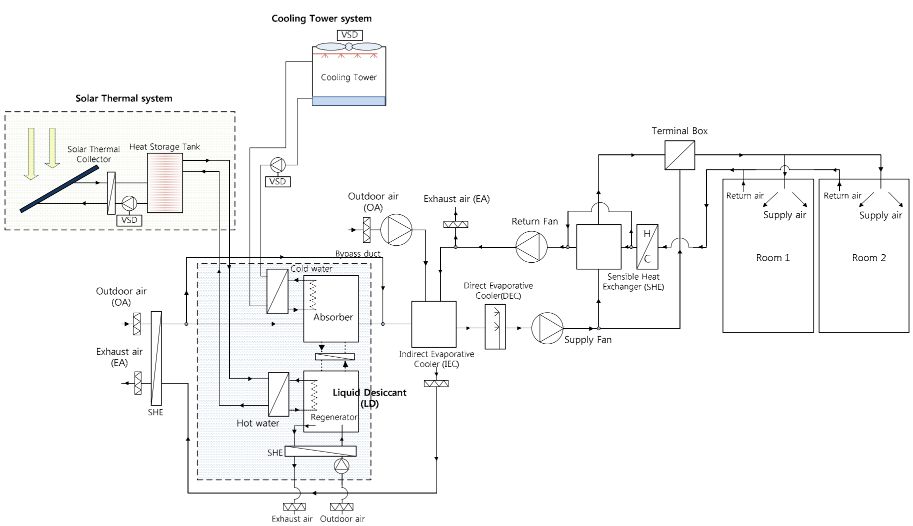


Figure 4. LD-IDECOAS configuration

***Liquid desiccant system (LD):*** The LD is operated when the temperature of outdoor air is above 13C and humidity ratio of outdoor air is high (i.e. Region A in mode of operation). The temperature of desiccant supplied to desiccant part of LD is maintained at 25~30C by operating the cooling tower. Cooling tower consumes fan and pump energy. Solar water heating system is used to maintain the temperature of desiccant introduced into regeneration part at 50~60C. In order to control the outlet humidity ratio of supply air, the amount of solution flow rate represented by the ratio of the liquid solution to supply air (LG ratio) into desiccant part is controlled.

***Indirect evaporative cooler (IEC):*** If the temperature of outdoor air is above 13C, it is operated at the maximum cooling effectiveness by spraying water into secondary side. If the temperature of outdoor air is below 13C, it acts as the role of sensible heat exchanger to pre-heat the introduced outdoor air without spraying water in secondary side.

***Direct evaporative cooler (DEC):*** If the temperature of outdoor air is more than 13C, humidification cooling operation is conducted to maintain the air which passes through LD and IEC at 13C.

***Heating coil (HC):*** In heating season, when the temperature of supply air cannot be met at 20C by heat recovery of IEC and SHE, HC is operated to maintain the target supply air temperature.

***Neutral and cold deck:*** When the outdoor air is greater than 13C and the minimum amount of ventilation is introduced due to small indoor cooling load, the temperature of supply air is increased from 13C to 20C upon decrease of space-cooling load. In order to achieve the heating of supply air, the portion of supplying the air to the neutral deck, which heat is recovered from return air, is increased by controlling the damper.

***Fan (main):*** It is operated to modulate the flow rate of supply air based on the space cooling load. When space cooling load is small in intermediate season and the proposed system is operated in heating season, fan is operated at the required minimum ventilation rate.

## 5. Simulation results

### 5.1 System flow on psychrometrics

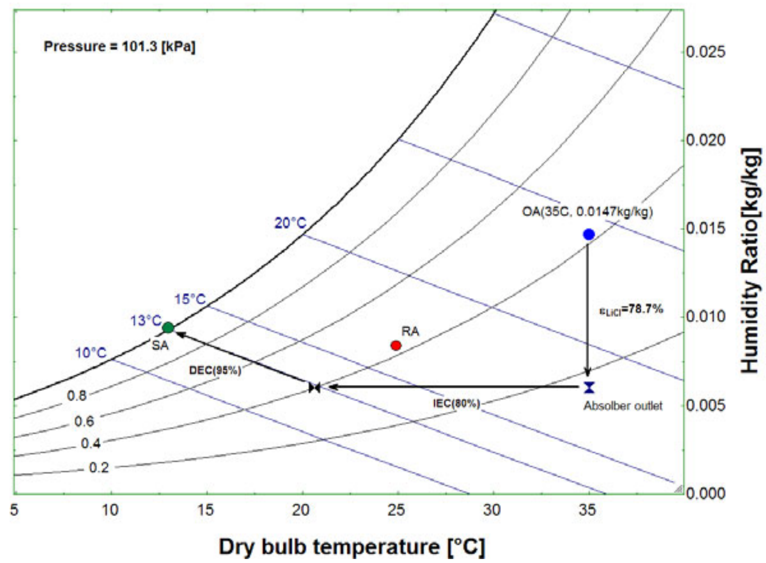


Figure 5. Dehumidification evaporative cooling system flow on psychrometrics

Figure 5 represents system performance on psychrometrics of desiccant and evaporative cooling based 100% outdoor air system applying liquid desiccant system. If LG ratio is 1 upon the use of LiCl solution, absolute humidity is dehumidified to 0.0060kg/kg with dehumidification effectiveness of 78.7%. As it passes through IEC, some of sensible heat load is removed through indirect evaporative cooling with effectiveness of 80% and some humidity is added through DEC with effectiveness of 95%. However, the proper temperature and humidity condition of supply air is maintained through evaporative cooling.

### 5.2 Comparison of energy consumption

#### 5.2.1 Comparison of annual and monthly operating energy consumption

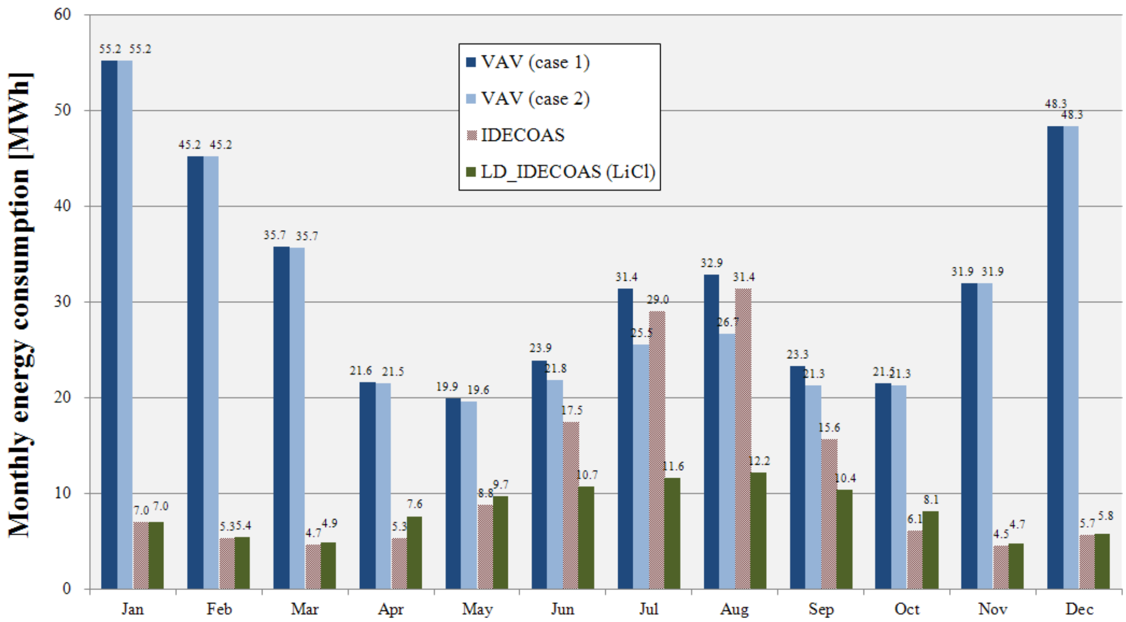


Figure 6. Comparison of annual operating energy consumption

As shown in Figure 6, when monthly energy consumption of LD-IDECOAS applying LiCl was compared with that of conventional VAV system, higher energy reduction was shown in every month compared to conventional VAV system. As a result, LD-IDECOAS system using LiCl as desiccant solution showed energy reduction by 74~75% compared to conventional VAV system.

Conventional IDECOAS reduced annual energy by 56~58% compared to conventional VAV system, but Figure 6 showed low performance in the peak cooling season (i.e. Jul, Aug). However, energy reduction was effectively made in the peak cooling season through LD-IDECOAS system. Even if it was implemented as eco-friendly HVAC system without using conventional cooling coil, annual operating energy of LD-IDECOAS was shown in 16~21% with respect to the existing IDECOAS. In LD-IDECOAS system shows that the operating energy almost not consumed except the fan energy. Therefore, it proved high possibility as next generation eco-friendly HVAC system.

Based on this result, if the conventional system was replaced or used by LD-IDECOAS system, proper indoor temperature and humidity condition can be maintained only with approximately 25% of annual operation energy.

## 6. Conclusion

In this study, decoupled system was configured to be separately responsible for dehumidification load and sensible load of outdoor air by applying liquid desiccant system and evaporative cooling system without using cooling coil in the cooling season. Based on this system, eco-friendly desiccant and evaporative cooling based 100% outdoor air system to control thermal indoor environment using 100% outdoor air was developed and system operating control method based on outdoor air condition was configured. Annual energy performance of IDECOAS developed through previous studies and

conventional VAV system was compared and analyzed through dynamic simulation,
As a result, the energy reduction effect of 87~89% was shown in the heating season compared to conventional VAV system. Energy reduction of 49~53% and 53~63% was shown in the intermediate and cooling seasons, respectively. Thus when LiCl desiccant solution was used, it was found that 74~75% of annual operating energy can be saved with respect to the conventional systems.
It was found that high energy reduction of 81~89% was made in the cooling season by replacing the cooling coil in conventional vapor-compressor manner. Through this manner, it was thought that the disadvantage of fan energy was sufficiently compensated and the possibility to implement eco-friendly low energy air conditioning system and furthermore zero or net-zero energy HVAC system has been increased. The research about energy saving potential of the proposed system through empirical study with prototype system will be carried out.

## Acknowledgement

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# A simplified model for predicting dehumidification effectiveness of a liquid desiccant system

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## Abstract
The main purpose of this research is to propose a practical correlation returning the dehumidification effectiveness of a liquid desiccant system. From the existing literature, it was found that two desiccant solutions; lithium chloride(LiCl), and triethylene glycol (TEG) solutions are commonly used as a working fluid in two different types of absorber towers; packed bed, and spray towers. In this research, the experimental data of each absorber tower performance with two different desiccant solutions were collected from the open literature. By statistically analyzing the collected data using the $2^k$ factorial experiment design approach, the impact of each system operation parameters on the dehumidification effectiveness were quantitatively estimated. And then, a simplified second-order equation model was derived as a function of operation parameters showing significant impact on the dehumidification effectiveness. It was found that the operating parameters, such as inlet ambient air temperature, desiccant solution temperature, liquid-to-gas ratio(L/G), inlet air relative humidity, and solution concentration have significant impact on the system dehumidification performance. The proposed model was validated by comparing the dehumidification effectiveness values predicted by both proposed model and existing models found in the existing literature.

Keywords: Liquid desiccant, LiCl, TEG, Packed tower, Spray tower

## 1. Introduction

In the conventional cooling process, the sensible and latent loads of a building should be controlled at the same time. Especially, the latent load should not be overlooked for realizing comfortable and healthy indoor environment during the humid climate zone, while it may require significant energy consumption. Liquid desiccant air conditioning systems are being considered as a reliable alternative to the conventional air conditioning system which is passively controlling the latent load of the building.
In the open literature, the dehumidification effectiveness prediction models for a liquid desiccant system have been proposed for the last several decades. However, they were derived from the theoretical or experimental analysis based on the heat and mass transfer which is expressed as complex equations. Therefore, this study proposes a simplified or practical model returning the dehumidification effectiveness of a liquid desiccant system as a function of five physical parameters which have significant impact on the system

performance. The proposed model is derived by statistically analyzing the performance data acquired from the open literature and simulations. The lithium chloride (LiCl) and the triethylene glycol (TEG) solutions, the most common liquid desiccants used in a packed tower or a spray tower type dehumidification system are considered as working fluids. By comparing dehumidification effectiveness values acquired from the proposed model and existing models found from the open literature, the reliability of the proposed model is verified.

## 2. Literature review

A spray tower liquid desiccant system using the TEG solution was proposed by Queiroz et al. (1988). Chung and Wu (1998, 2000) estimated the dehumidification effectiveness of the spray tower through a series of experiments, and derived an analytical model based on the heat and mass transfer. Lai et al. (2003) rated the impact of some selected operating parameters of the spray tower liquid desiccant system using the TEG solution by statistically analyzing their experimental data.

On the other hand, Chung et al. (1994, 1996, 1999, 2000) proposed an analytical model for predicting the dehumidification effectiveness of the packed tower liquid desiccant system with the TEG solution. Fumo and Goswami (2002) checked the moisture removal rate in the packed bed tower with the LiCl solution through experiments. They also suggested an equation returning the vapor pressure of aqueous solution at each absorption and regeneration stage. Zurigat et al. (2004) also performed experiments for getting the dehumidification effectiveness data of packed bed tower with TEG solution. Their system used the wood packing and the aluminum packing, and the experiment results were compared with the existing model proposed by Chung and Luo(1999).

Longo and Gasparella (2005) did more comprehensive experiments to see the changes of the moisture level of the process air following the variation of the desiccant solution concentration and the kind of desiccant solutions (e.g. LiCl, LiBr and KCOOH solutions). Jain et al.(2000, 2007, 2011) performed detailed comparison of common three desiccant solutions (e.g. LiCl, $CaCl_2$, and TEG) applied to the packed bed tower. In addition, Jain and Bansal (2007) analyzed the impact of the physical variables considered in each pervious experiment on the system performance, and then compared the dehumidification effectiveness acquired from the experiments with the predicted values of their proposed model.

## 3. Liquid Desiccant Systems

A liquid desiccant system responds to the latent heat load during the operation of the air conditioning system by absorbing moisture from the supply air (or process air) using chemical reactions between the desiccant solution and the process air. The moisture transfer process between two substances is caused by the vapor pressure differences. Especially, the vapor pressure of the desiccant solution at a given temperature may provide significant impact on the desiccant system's performance.

In general, liquid dehumidifiers commonly used in our industry are largely classified into two types; that is, the spray tower type and the packed tower type systems (Fig. 2).

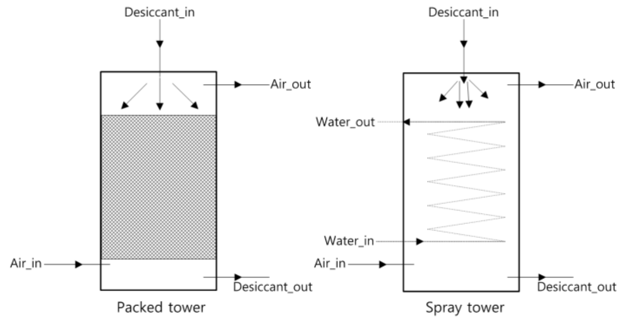


Fig. 2. Schematic diagram of the liquid desiccant dehumidifiers

The dehumidification effectiveness of the liquid desiccant system is a ratio of the humidity ratio variation of the process air over the humidity ratio difference between the inlet air and the equilibrium humidity ratio of the desiccant solution (Eq. 1).

$$\varepsilon_y = \frac{\omega_{inlet} - \omega_{outlet}}{\omega_{inlet} - \omega_{equ}} \quad (1)$$

Where, $\varepsilon_y$: dehumidification effectiveness [%]
$\omega_{inlet}$: inlet air humidity ratio [kg/kg],
$\omega_{outlet}$: outlet air humidity ratio [kg/kg]
$\omega_{equ}$: humidity ratio at equilibrium of desiccant solution [kg/kg]

The equilibrium humidity ratio of the desiccant solution is the humidity ratio at which the moisture is not absorbed any more.

## 4. Dehumidification Effectiveness Prediction Model

The dehumidification effectiveness prediction models for the packed tower and the spray tower type liquid desiccant systems were developed by statistically analyzing the performance data collected from the open literature. Using the $2^k$ factorial experiment design method, the five operating parameters which show significant impacts on the liquid desiccant system performance were identified (Eq.2). And then the second-order correlation for returning the dehumidification effectiveness of the liquid desiccant system was derived as a function of those selected design parameters.

$$\varepsilon_y = f\,(L/G, T_{ai}, T_{si}, \omega_{ai}, X_{si}) \quad (2)$$

Where, L/G: liquid-to-gas ratio
$T_{in}$: inlet air temperature [°C]
$T_{si}$: outlet solution temperature [°C]
$\omega_{ai}$: inlet air humidity ratio [kg/kg]
$X_{si}$: inlet solution concentration [%]

### 4.1 Packed tower model

The proposed model considers both LiCl and TEG solutions. Table 1 shows the impact (or contribution) of each selected parameters and their combinations on the dependent parameter (i.e. the dehumidification effectiveness) estimated using Design Expert 8.0 software. The second-order polynomial shown in Equation 3 is the proposed model for predicting the dehumidification effectiveness based on the operating conditions of the process air and the desiccant solution. The model coefficients are summarized in Table 2.

Table 1. Impact of model parameters (Packed tower)

| Variable | $L/G$ | $T_{ai}$ | $\omega_{ai}$ | $T_{si}$ | $X_{si}$ | $L/G\cdot T_{ai}$ |
|---|---|---|---|---|---|---|
| Contribution(%) | 17% | 11.3% | 5% | 0.5% | 7% | 1.6% |
| Variable | $L/G\cdot\omega_{ai}$ | $L/G\cdot T_{si}$ | $L/G\cdot X_{si}$ | $T_{ai}\cdot\omega_{ai}$ | $T_{ai}\cdot T_{si}$ | $T_{ai}\cdot X_{si}$ |
| Contribution(%) | 1.7% | 5.4% | 9.4% | 18% | 15.9% | 2.6% |
| Variable | $W_{ai}\cdot T_{si}$ | $W_{ai}\cdot X_{si}$ | $T_{si}\cdot X_{si}$ | $L/G^2$ | $T_{ai}^2$ | $\omega_{ai}^2$ |
| Contribution(%) | 2.1% | 0.26% | 7.3% | 6.3% | 3.1% | 2.3% |
| Variable | $T_{si}^2$ | $X_{si}^2$ | | | | |
| Contribution(%) | 29.5% | 22.7% | | | | |

$$\varepsilon\_y = \alpha_0 + \alpha_1(L/G) + \alpha_2(T_{ai}) + \alpha_3(\omega_{ai}) + \alpha_4(T_{si}) + \alpha_5(X_{si}) + \alpha_6(L/G\cdot T_{ai}) + \alpha_7(L/G\cdot\omega_{ai}) + \alpha_8(L/G\cdot T_{si}) + \alpha_9(L/G\cdot X_{si}) + \alpha_{10}(T_{ai}\cdot\omega_{ai}) + \alpha_{11}(T_{ai}\cdot T_{si}) + \alpha_{12}(T_{ai}\cdot X_{si}) + \alpha_{13}(\omega_{ai}\cdot T_{si}) + \alpha_{14}(\omega_{ai}\cdot X_{si}) + \alpha_{15}(T_{si}\cdot X_{si}) + \alpha_{16}(L/G^2) + \alpha_{17}(T_{ai}^2) + \alpha_{18}(\omega_{ai}^2) + \alpha_{19}(T_{si}^2) + \alpha_{20}(X_{si}^2) \quad (3)$$

Table 2. Model coefficients (Packed tower)

| $\alpha_0$ | $\alpha_1$ | $\alpha_2$ | $\alpha_3$ | $\alpha_4$ | $\alpha_5$ |
|---|---|---|---|---|---|
| +0.3998 | -0.3233 | -0.0224 | -14.8076 | +0.0845 | -0.5270 |
| $\alpha_6$ | $\alpha_7$ | $\alpha_8$ | $\alpha_9$ | $\alpha_{10}$ | $\alpha_{11}$ |
| +0.0035 | +5.7279 | +0.0034 | +0.3147 | +4.8348 | -0.0048 |
| $\alpha_{12}$ | $\alpha_{13}$ | $\alpha_{14}$ | $\alpha_{15}$ | $\alpha_{16}$ | $\alpha_{17}$ |
| +0.0447 | -3.2790 | +20.4259 | +0.0279 | -0.0074 | +0.0006 |
| $\alpha_{18}$ | $\alpha_{19}$ | $\alpha_{20}$ | | | |
| -1698.36 | +0.0016 | -1.7716 | | | |

Figure 3(a) is the normal probability distribution of the proposed model for the packed tower system. It shows that the selected parameters represent the packed tower system characteristic well. The $R^2$-value of the proposed model is 0.98.

### 4.2 Spray tower model

The proposed model for the spray tower with the TEG solution has also been derived by the same statistical approach. Table 3 shows the contribution of each selected parameters and their combinations on the dehumidification effectiveness. Equation 4 is the proposed model for returning the dehumidification effectiveness based on the operating conditions of the process air and the desiccant solution. The model coefficients are summarized in

Table 4.

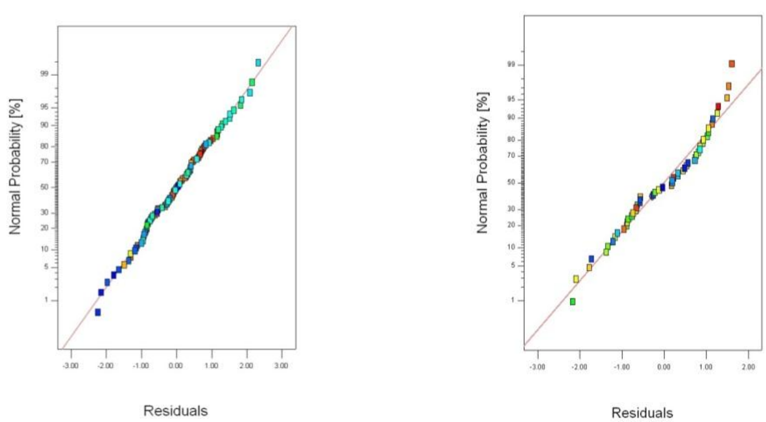
Table 3. Impact of model parameters (Spray tower)

| Variable | $L/G$ | $T_{ai}$ | $\omega_{ai}$ | $T_{si}$ | $X_{si}$ | $L/G \cdot T_{ai}$ |
|---|---|---|---|---|---|---|
| Contribution(%) | 37.5% | 62.5% | 65.4% | 28% | 57.6% | 18.7% |
| Variable | $L/G \cdot \omega_{ai}$ | $L/G \cdot T_{si}$ | $L/G \cdot X_{si}$ | $T_{ai} \cdot \omega_{ai}$ | $T_{ai} \cdot T_{si}$ | $T_{ai} \cdot X_{si}$ |
| Contribution(%) | 12.5% | 1.25% | 20.6% | 7.5% | 56% | 2.2% |
| Variable | $\omega_{ai} \cdot T_{si}$ | $\omega_{ai} \cdot X_{si}$ | $T_{si} \cdot X_{si}$ | $L/G^2$ | $T_{ai}^2$ | $\omega_{ai}^2$ |
| Contribution(%) | 18.7% | 13.8% | 19.3% | 3.7% | 0.4% | 37.5% |
| Variable | $T_{si}^2$ | $X_{si}^2$ | | | | |
| Contribution(%) | 33.7% | 42.3% | | | | |

$$\varepsilon\_y = \beta_0 + \beta_1(L/G) + \beta_2(T_{ai}) + \beta_3(\omega_{ai}) + \beta_4(T_{si}) + \beta_5(X_{si}) + \beta_6(L/G \cdot T_{ai}) + \beta_7(L/G \cdot \omega_{ai}) + \beta_8(L/G \cdot T_{si}) + \beta_9(L/G \cdot X_{si}) + \beta_{10}(T_{ai} \cdot \omega_{ai}) + \beta_{11}(T_{ai} \cdot T_{si}) + \beta_{12}(T_{ai} \cdot X_{si}) + \beta_{13}(\omega_{ai} \cdot T_{si}) + \beta_{14}(\omega_{ai} \cdot X_{si}) + \beta_{15}(T_{si} \cdot X_{si}) + \beta_{16}(L/G^2) + \beta_{17}(T_{ai}^2) + \beta_{18}(\omega_{ai}^2) + \beta_{19}(T_{si}^2) + \beta_{20}(X_{si}^2) \quad (4)$$

Table 4. Model coefficient (Spray tower)

| $\beta_0$ | $\beta_1$ | $\beta_2$ | $\beta_3$ | $\beta_4$ | $\beta_5$ |
|---|---|---|---|---|---|
| -116.98 | +15.351 | -1.659 | -3821.71 | +4.883 | +214.271 |
| $\beta_6$ | $\beta_7$ | $\beta_8$ | $\beta_9$ | $\beta_{10}$ | $\beta_{11}$ |
| -0.035 | -70.409 | +0.035 | -15.361 | +31.031 | -0.011 |
| $\beta_{12}$ | $\beta_{13}$ | $\beta_{14}$ | $\beta_{15}$ | $\beta_{16}$ | $\beta_{17}$ |
| +2.196 | -18.054 | +3536.161 | -4.831 | +0.179 | -0.012 |
| $\beta_{18}$ | $\beta_{19}$ | $\beta_{20}$ | | | |
| +7835.932 | +0.004 | -101.271 | | | |




(a) Packed tower model (b) Spray tower model

Fig. 3. Normal probability plots

Figure 3(b) is the normal probability plot of the spray tower model. It shows that the selected parameters represent well the packed tower system characteristic. The $R^2$-value of the proposed model is 0.98.

### 4.3 Reliability of the proposed correlations

The dehumidification effectiveness values of the packed tower system were determined by the proposed model (i.e. Eq. 3) for the various liquid-to-gas ratios and inlet air humidity ratios. It was assumed that the LiCl or the TEG solution was used for the desiccant system. And then, the model predicted values were compared with the data found in the existing literature for verifying the reliability of the proposed model.

In Figures 5 and 6, one may see that the variation curves of the dehumidification effectiveness predicted by the proposed model with the increase of L/G or $T_{ai}$ follow the existing research results relatively well.

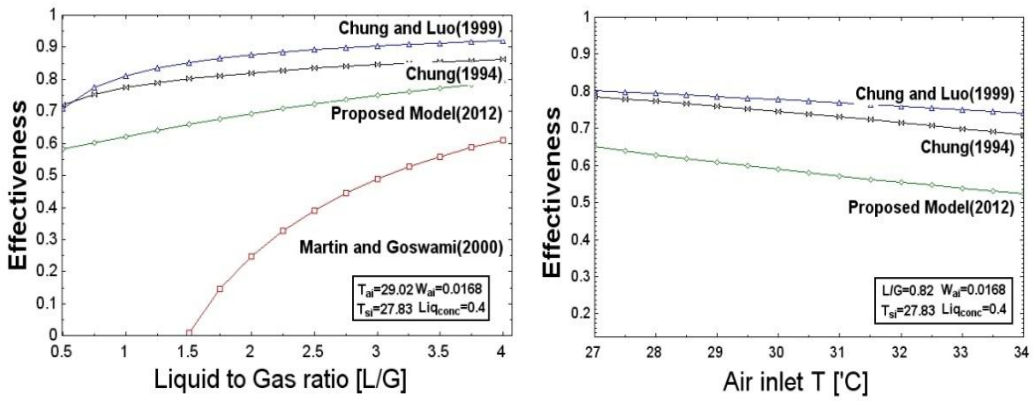



Fig. 5. Effect of L/G and $T_{ai}$ on the packed tower effectiveness (LiCl)

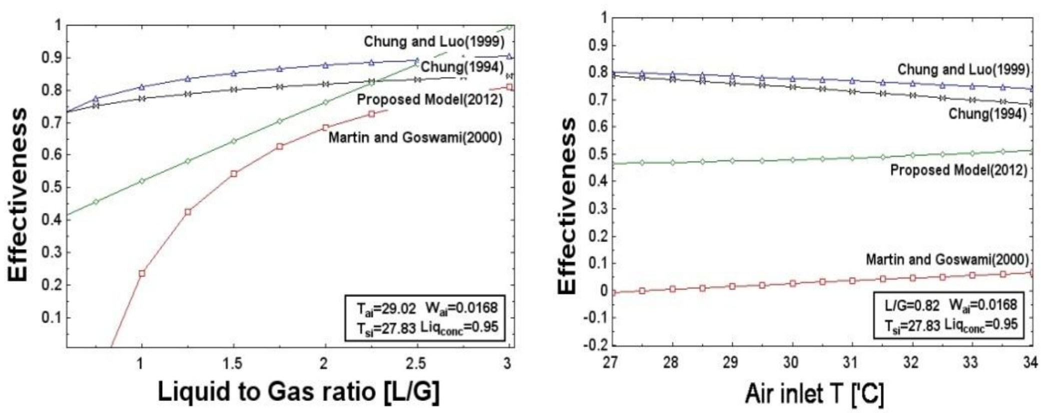



Fig. 6. Effect of L/G and $T_{ai}$ on the packed tower effectiveness (TEG)

On the other hand, the dehumidification effectiveness values of the spray tower system were also estimated by the proposed model (i.e. Eq. 4) with increasing liquid-to-gas ratio and inlet air humidity ratio. The model predicted values were compared with the experimental data found in the open literature (Chung (1998, 2000)). Figure 7 shows that the model predicted effectiveness follows the experimental data relatively well.

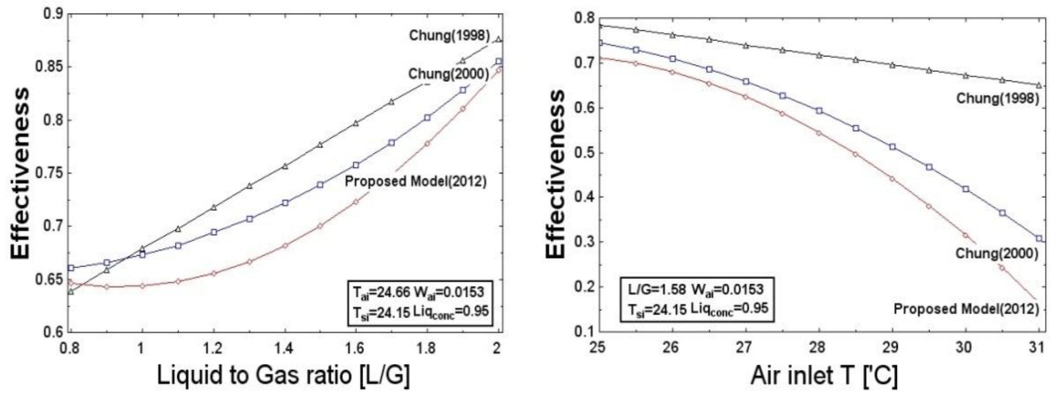



Fig. 7. Effect of L/G and $T_{ai}$ on the spray tower effectiveness (TEG)

## 5. Conclusions

The simple second-order polynomials returning the dehumidification effectiveness of the packed tower or spray tower liquid desiccant system have been proposed in this research. Although the dehumidification process in a liquid desiccant system is governed by intricate heat and mass transfer, it was found that the dehumidification effectiveness of the conventional liquid desiccant system might be represented more simply by five operational parameters; liquid-to-gas ratio, process air inlet temperature and humidity ratio, and initial concentration and outlet temperature of the desiccant solution.

The reliability of the proposed model was checked using the performance data acquired from the open literature. The variation trend of the predicted effectiveness follows the established experimental research results relatively well, while they do not match perfectly.

## Acknowledgement

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# Energy saving potentials of demand-controlled ventilation based on real-time traffic load in underground parking facilities

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## Abstract
The main topic of this paper is to show a possibility of indoor air quality enhancement and the fan energy savings in underground parking facilities by applying the demand-controlled ventilation (DCV) strategy based on the real-time variation of the traffic load. The established ventilation rate is estimated by considering the passing distance, CO emission rate, idling time of a vehicle, and the floor area of the parking facility. However, they are hard to be integrated into the real-time DCV control. As a solution to this problem, the minimum ventilation rate per a single vehicle is derived in this research based on the actual ventilation data acquired from several existing underground parking facilities. And then its applicability to the DCV based on the real-time variation of the traffic load is verified by simulating the real-time carbon monoxide concentration variation. The energy saving potentials of the proposed DCV strategy is also checked by comparing it with those for the current underground parking facility ventilation systems found in the open literature.

Keywords: demand controlled ventilation, energy conservation, underground parking facilities, vehicle detection system

## 1. Introduction

For the last several decades, the development of demand-controlled ventilation (DCV) approach has been commonly focused on occupant spaces, while little attention has been paid on non-occupant spaces such as underground parking facilities (Chao et al., 2004; Jeong et al 2010).

According to established ventilation standards (Table 1), many countries defined the minimum outdoor air ventilation rate required for keeping the carbon monoxide (i.e. CO) concentration to a certain maximum allowable level (Krarti et al., 2001). Each recommended ventilation rate is normalized for the unit floor area or unit volume of the facility, so applying current ventilation standard for parking facilities to the DCV control based on the real-time variation of the traffic load may be difficult.

In this research, a minimum ventilation air flow required for a single vehicle is derived based on current ventilation standard and operation data acquired from several open literature for underground parking facilities in Korea, which can be more easily integrated into the DCV control approach. The possibility of indoor air quality (IAQ) enhancement and fan energy savings by the DCV strategy is also quantitatively analyzed by the simulation study.

Table 1.Ventilation rates for enclosed parking garages

| | Canada | Finland | Germany | Korea | Singapore | U.K | U.S.A |
|---|---|---|---|---|---|---|---|
| Period [h] | 8/1* | 8/0.25[a] | - | 8 | - | 8/0.25[a] | 8/1[a] |
| CO[ppm] | 11-13 /25-30** | 30/75[b] | - | 25 | 25 | 50/300[b] | 9/35[b] |
| Ventilation rate | - | 9.72 [$m^3$/h-$m^2$] | 11.88 [$m^3$/h-$m^2$] | 27 [$m^3$/h-$m^2$] | 9 [$m^3$/$m^3$-h] | 6 - 10 [$m^3$/$m^3$-h] | 27.36 [$m^3$/h-$m^2$] |

*Note:* *8hour or 1hour, **11-13ppm or 25-30ppm. (e.g. 8hour exposure limitation is 11 – 13 ppm, and 1 hourlimitation is 25-30ppm in Canada)*

## 2. Ventilation Modes

The existing operation modes of the mechanical ventilation applicable to a parking facility are continuous operation and intermittent operation.

### 2.1 Continuous operation

Continuous operation mode is the constant or fixed volume supply of the ventilation air. It is appropriate for parking facilities with the high usage (or circulation) rate. Because of the continuous operation of ventilation units, relatively high fan energy consumption is inevitable. As for this case, two different DCV approaches; CO-concentration based DCV (CO-DCV) and DCV with vehicle detection system (VDS-DCV) are proposed to reduce the fan energy consumption.

(1)CO-DCV

The CO-DCV uses CO detection system for estimating real-time variation of the traffic load by monitoring the indoor CO concentration variation, and modulating the ventilation rate. Recently, the use of CO sensor in underground parking facilities has been widely induced due to cost-effective sensors available (Stipe., 2003). The number of vehicles in the facility can be estimated indirectly from the transient variation of the CO concentration.

(2)VDS-DCV

The VDS-DCV is based on the actual number of vehicles monitored by the detecting sensors (or cameras) installed at the entrance and the exit of the parking facility. Based on the real-time variation of the traffic load, one can adjust the ventilation rate.

### 2.2. Intermittent operation

In the intermittent operation mode for the underground parking facilities is the simple on/off (or binary) control of the mechanical ventilation system, and VDS-DCV can also be integrated.

(1) Simple binary control
When the indoor CO concentration reaches at its upper limit level, constant volume ventilation units are activated and supply design flow until the CO concentration is back to normal. This simple approach is suitable for the facility with insignificant fluctuation of entering and leaving vehicles.

(2)VDS-DCV
In the VDS-DCV, the VDS is monitoring the number of vehicles in the facility. When the CO concentration increases over the upper limit, the ventilation units begin to supply exact amount of ventilation air determined based on the number of vehicles detected at that moment.

## 3. DCV Simulation

From the existing literature providing actual ventilation data measured for various underground parking facilities (Fig. 1), the average ventilation rate per a vehicle has been estimated; that is, 622m$^3$/hr-car.

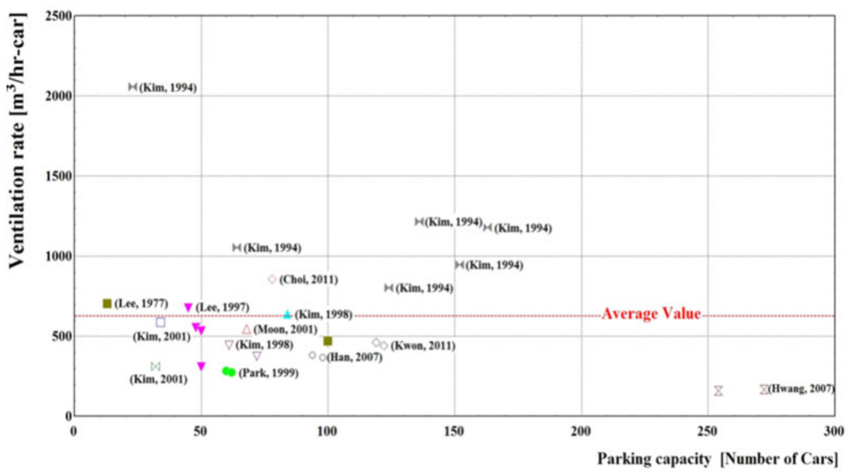



Fig.1. Ventilation rate per a vehicle acquired from open literature

The transient CO concentration variation inside the facility is expressed by Equation 1. By rearranging the governing equation for the transient variation of the number of vehicles (i.e. $N_e/dt$), and then discretizing the equation for the time (Eq. 2), one may estimate the number of vehicles based on the CO concentration variation. The predicted number of vehicles is a critical input parameter in the CO-DCV operation. The discrete governing equation has been solved numerically using a commercial equation solver program.

$$V\frac{dC}{dt} = -Q_s(C - C_s) + \left(E \times \nu \times \theta \times \frac{N_e}{dt}\right) \quad (1)$$

$$\left(\frac{N_e}{dt}\right)^n = \frac{1}{(E\times\nu\times\theta)}\left[V\frac{(C^n - C^{n-1})}{dt} + Q_s^n(C^n - C^{n-1})\right] \quad (2)$$

Where, $V$: the space volume, $m^3$
$dC/dt$: the time-variant change CO concentration, 1/min.
$Q_s$: the ventilation airflow rate, $m^3$/min.
C: the indoor CO concentration, $m^3/m^3$
$C_s$: the CO concentration of supply air, $m^3/m^3$
$E$: the average CO emission for a typical car, g/h-car
$\nu$: the specific volume of CO, $m^3$/kg
$\theta$: the average length of operation and travel time for a typical car, min
$N_e/dt$: the time-variant change number of cars, car/min
$dt$: the time interval, min
$n, n-1$: the current and previous time steps

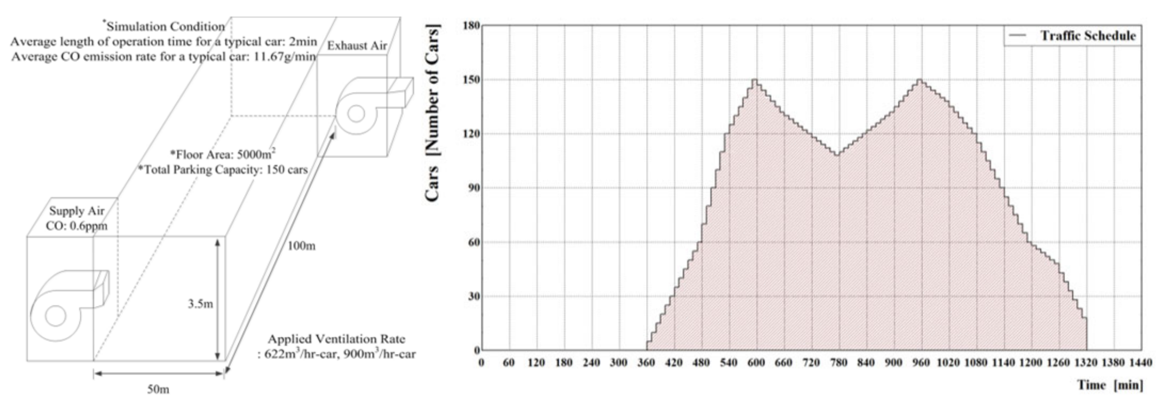
### 3.1. Simulation conditions

A 5000-$m^2$ space (100m×50m×3.5m) is defined as the model parking facility for ventilation control simulations. It is assumed that the model space is served by the supply and the exhaust air units with variable frequency drives (Fig. 2(a)). The impact of the natural ventilation is not considered for simplicity. The design parking density is 3cars/100$m^2$, so the model space is able to accommodate 150 vehicles.

The ambient air CO concentration is set to 0.6ppm (MEK, 2009). And the average length of operating time and the CO emission rate per a typical car are assumed as 2minutes, and 11.67g/min., respectively (ASHRAE 2007). Figure 2(b) is the traffic load schedule defined for the simulation.

The minimum required ventilation rate per a single vehicle acquired from the open literature is 622$m^3$/h-car. However, when the current Korean ventilation standard (i.e. 27$m^3$/h-$m^2$) is apply to the given space, the minimum ventilation rate becomes 900$m^3$/h-car. Therefore, the DCV simulations are performed using both minimum ventilation rates.

It is assumed that ventilation system is operated from 6:00AM to 22:00PM, and deactivated for the rest of the time. The static pressure for supply and exhaust fans is set to 500 Pa, and 1-kW power is required per 5000-CMH air supply.




(a) Model space (b) Traffic load schedule

Fig.**2**. Simulation conditions

### 3.2 Simulation results

The DCV simulations are performed for the continuous and the intermittent operations of the ventilation system of the model space. The CO-DCV and the VDS-DCV are applied to the continuous operation mode. As for the intermittent mode operation, to the simple binary control method and the VDS-DCV approach are considered.

(1)DCV for continuous operation

In Figure 3(a), one may see that the transient traffic load variation is predicted well in the CO-DCV cases with two different ventilation rates per a vehicle. The number of cars estimated indirectly from the indoor CO concentration variation match very close to the exact numbers from the vehicle detecting system, while there is a little delay and under estimation. It may be normal because the CO concentration variation always follows the traffic load changes.

The transient supply airflow rate variation estimated for each DCV strategy is presented in Figure 3(b). When the CO-DCV or the VDS-DCV approach is used, the ventilation airflow is modulated based on the predicted or exact number of vehicles inside the model space. Consequently, the total amount of ventilation air supplied to the space (i.e. the area under the line) in each DCV case is less than that for the constant volume control (CVC) case. In CVC cases, the required ventilation rate per a single vehicle is set to $622m^3$/h-car (i.e. average value from the open literature) or to $900m^3$/h-car (i.e. current Korean ventilation standard).

Figure 3(c) depicts the variation of the CO concentration for each ventilation strategy. One may see that all DCV cases can maintain the CO concentration below the threshold value (i.e. 25ppm), while the CVC operations lower the CO concentration somewhat quickly at the early stage of the mechanical ventilation. It means that both CO-DCV and VDS-DCV approaches can avoid the over-ventilation occurring in CVC operation.

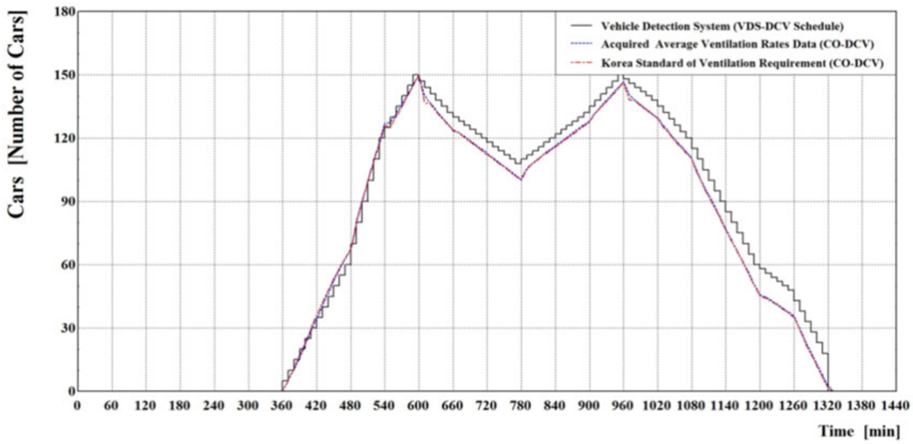
(2)DCV for intermittent operation

Figure 4 shows the results of the simple binary control and VDS-DCV simulations for the intermittent operation. The simple binary control supplies the design ventilation flow when the indoor CO concentration exceeds the threshold level (Fig. 4(a)), so the CO concentration drops quickly below the upper limit (Fig. 4(b)). However, it seems that the indoor CO concentration may also be maintained at acceptable level with less ventilation air by combining the VDS-DCV approach with the simple on-off control. As shown in Figure 4(a), the VDS-DCV adjusting the ventilation airflow based on the real-time traffic load whenever the indoor CO concentration is higher than its upper limit. Although the indoor CO concentration under the VDS-DCV control is a little higher than the simple on/off control case (Fig. 4(b)), it is still acceptable level.

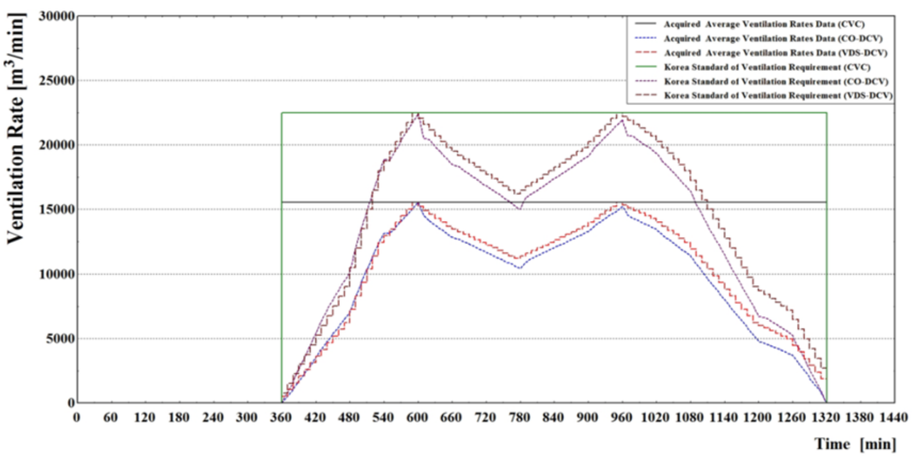
### 3.3. Impact of DCV controls

Figure 5 shows the average CO concentration and the fan energy consumption estimated for each DCV operation during the day. As expected, the average indoor CO concentrations of intermittent mode operation cases are higher than those of the continuous mode operation cases (Fig. 5(a)). In addition, the lowest CO concentration is observed under the CVC operation in both continuous and intermittent mode operations, while the VDS-DCV cases combined with the simple binary control show the highest indoor CO concentration. However, the threshold concentration of 25ppm has not been violated even in the worst average CO concentration case.

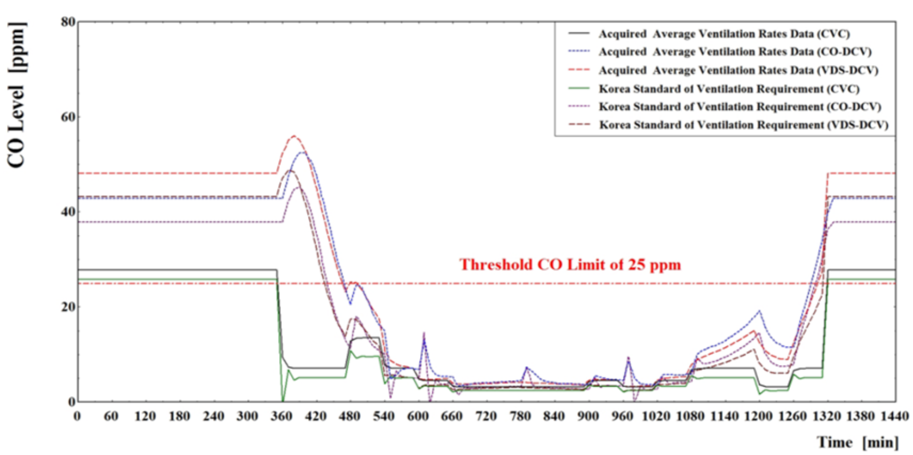
As for the fan energy consumption, the DCV cases in continuous mode operations save 33-37% of the fan energy with respect to the CVC case (Fig. 5(b)). One may also see that significant fan energy saving is possible with the simple binary control and the VDS-DCV in the intermittent operation, while the indoor CO concentration is relatively high.




(a) Traffic loads

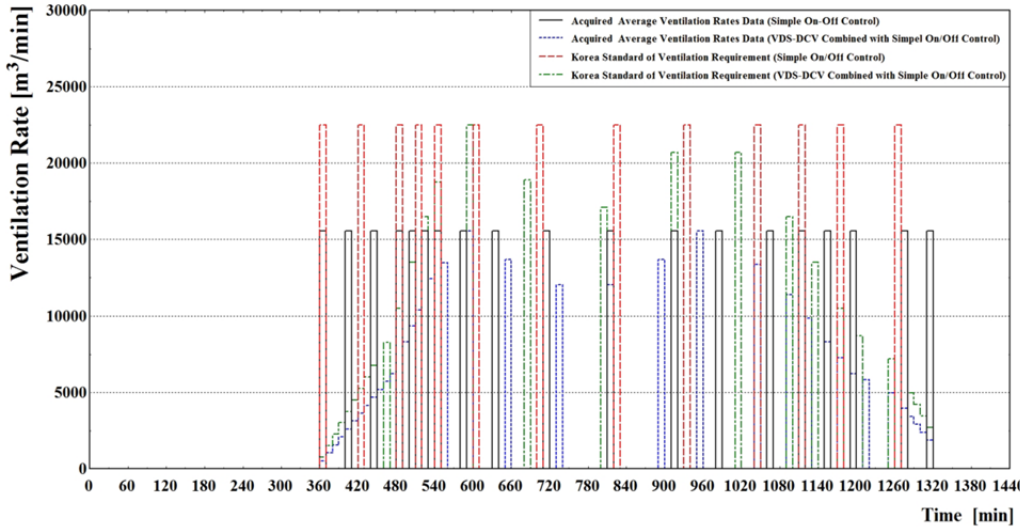



(b) Ventilation rate

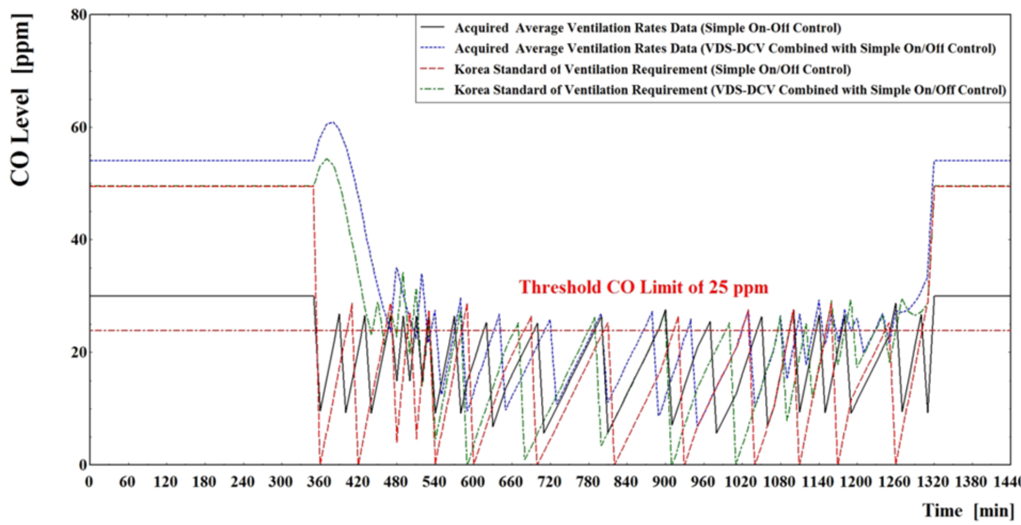



(c) CO Concentration

Fig.3. Continuous mode operation




(a) Ventilation rate

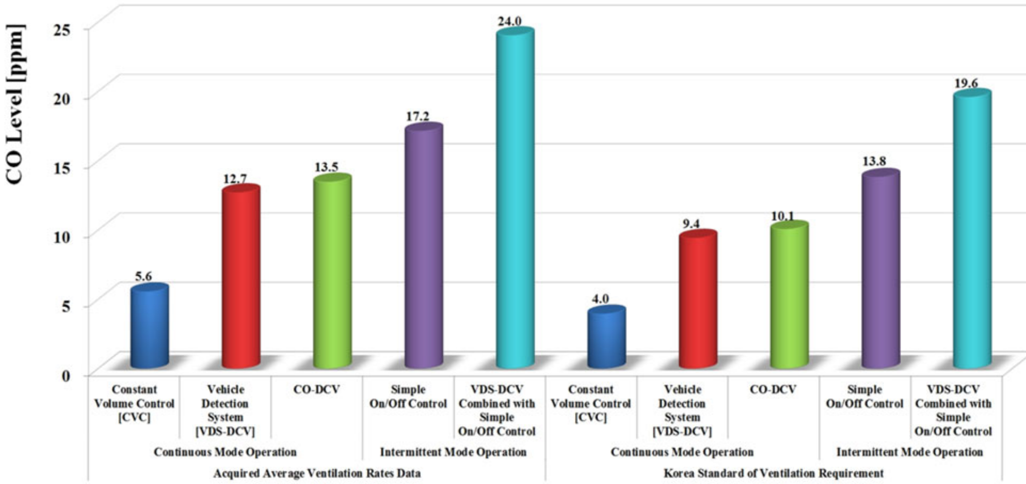



(b) CO concentration

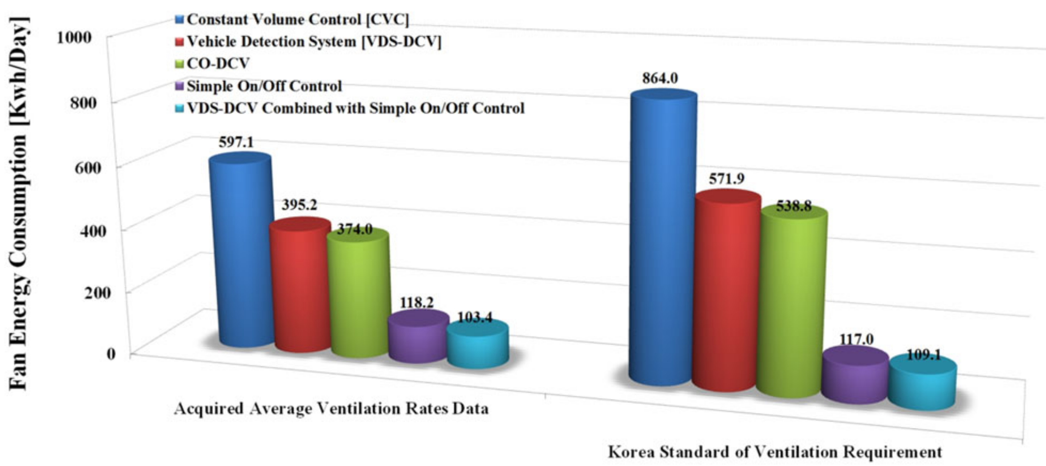
Fig.4.Intermittent mode operation

## 4. Conclusion

In this study, the current ventilation standards defined as the ventilation rate per floor area or air exchange rate in an underground parking facility was converted as a form of the ventilation rate per a single vehicle. And then the impact of several DCV strategies using the real-time traffic load on the indoor CO concentration and the fan energy consumption were quantitatively analyzed via a series of simulations. The simulation results indicate that a large amount of fan energy consumption can be reduced by the VDS-DCV method in both continuous and intermittent mode operations, in addition to the acceptable indoor air quality. The CO-DCV approach may also be a good choice in the continuous operation mode.




(a) Average CO concentration




(b) Fan energy consumption

Fig.5.Impact of DCV controls

In case of the intermittent operation, significant fan energy savings were observed in both the simple binary control and the VDS-DCV, but one may experience the degradation of indoor air quality. Consequently, the continuous operation of ventilation units based on the CO-DCV or VDS-DCV may be a good choice for achieving energy savings and good indoor air quality simultaneously.

## Acknowledgement

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# CREATING "AS-OPERATED" WHOLE-BUILDING ENERGY MODELS FOR EXISTING COMMERCIAL MEDIUM SIZED OFFICE BUILDINGS-A CASE STUDY

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## ABSTRACT
Before a dynamic, whole-building energy model (BEM) can be used to evaluate proposed energy conservation measures (ECMs) with reasonable certainty, it must be constructed and calibrated with metered site data to a predetermined level of fidelity using the existing building's actual operation conditions. In practice, ASHRAE level I or II energy audits are used to initiate a building retrofit project. Recorded variables and building operation measurements, particularly energy use associated with specific end use functionalities that are subsequently used as BEM inputs, can significantly impact the model's accuracy. Therefore, to efficiently establish a precise model, it is necessary to identify the minimum instrumentation and measurements needed to calibrate the BEM to the level of fidelity required for significant ECM to be specified, prioritized and implemented. This paper describes case studies of constructing and well-tuning EnergyPlus BEMs to "as-operated" conditions for two medium size office buildings located in Mid-Atlantic region (Climate Zone 4A). Guided by a prioritized, key parameter list generated through an EnergyPlus BEM sensitivity study, information collected from the buildings "as-built" drawings, the building automation system (BAS) sequence of operation documents, screenshots of the BAS interfaces, together with hourly sub-metering data and a short two-hour site visit are used to develop the "as-operated" BEMs. The actual meteorological year (AMY) weather file is used to perform real-time simulations and the simulated building energy use is then compared to the actual building monthly utility bills and sub-metered hourly energy data.

## KEYWORDS
Whole Building Energy Model, EnergyPlus, Office Building, Minimum Instrumentation

## INTRODUCTION

During more than forty-years of uninterrupted development, the number of whole-building energy simulation programs continues to increase (Ayres and Stamper, 1995) and simulation capabilities have evolved from simple, single formula estimates to complex, high-fidelity simulations of buildings on a room-by-room basis (Sowell and Hittle, 1995, Crawley et al., 2008). The relatively recent prevalent green building labelling and rating systems such as Leadership in Energy and Environmental Design (LEED) launched by U.S. Green Building Council (USGBC), has encouraged the use of building energy simulation tools for new building design by assigning a maximum of 19 credits to demonstrate optimized building energy performance proven by a whole building energy simulation (USGBC, 2010). Simulation results of “as-designed” BEMs are compared to *virtual* “baseline” models, which are thoroughly defined by national/local energy codes, such as ASHRAE Standard 90.1, to evaluate the current design energy use. However, a follow up study (Turner and Frankel, 2008) shows the measured energy use of 121 self-reported LEED certified buildings suggests the ratio of “measured to designed building site energy use intensity (EUI)” scatters from less than 0.5 to more than 2.75, indicating substantial inconsistency between “as-designed” BEM assumptions and actual operations. Therefore, creating “as-operated” BEMs for existing commercial buildings, that is, “reconciling” as-designed BEMs to the actual building operation conditions would be the first crucial step to assess potential ECMs. Numerous investigations and case studies about both manual, heuristic model calibration approaches (Kaplan et al., 1990, Waltz, 1992, Norford et al., 1994, Haberl and Bou-Saada, 1998, Yoon and Lee, 1999, Pan et al., 2007) and mathematical, analytical methods (Carroll and Hitchcock, 1993, Lee and Claridge, 2002, Reddy et al., 2006) are reported. Nevertheless, the lack of a standardized model tuning methodology - short of complete building sub-metering data and recording of operation variables - taken along with the fact that every building is designed and operated differently, makes BEM as-designed to as-operated reconciliation a tedious, labour-intensive task.

This study investigates the minimum instrumentation required to gather key building operational information during level I and II energy audits to construct “as-operated” BEMs for two medium sized office buildings in the Philadelphia region. The results clearly indicate the desirability of having such sub-metering specified as an integral part of any new construction to enable continuous model adjustments as building internal use changes and quantitatively identify potential ECM’s in time.

## METHODOLOGY

Ideally, to build an “as-operated” model, all input variables should be measured and verified in the existing building. However, in practice, it is very difficult to do so due to limited time and budgets available to the modeler. Thus sensitivity analysis (SA) technique, defined as a study of how uncertainty in the output of a model (numerical or otherwise) can be apportioned to different sources of uncertainty in the model input (Saltelli et al., 2000), is deployed to differentiate parameters having different levels of impact in the model. In a previous study (Xu and Freihaut, 2012), both building and system level input-output sensitivity coefficients of 50 selected parameters in DOE-reference medium size office building model are calculated and prioritized in descending order. A list of twenty parameters that are most sensitive to the whole building energy use in Climate Zone 4A, shown in Table 2, serves as guidance for data collection during the energy audits. Additional building information, such as design drawings, the building automation system (BAS) operation document, occupants' schedules, etc., is also provided by the owner. Five steps towards building up an "as-operated" BEM in this study are summarized in Figure1.

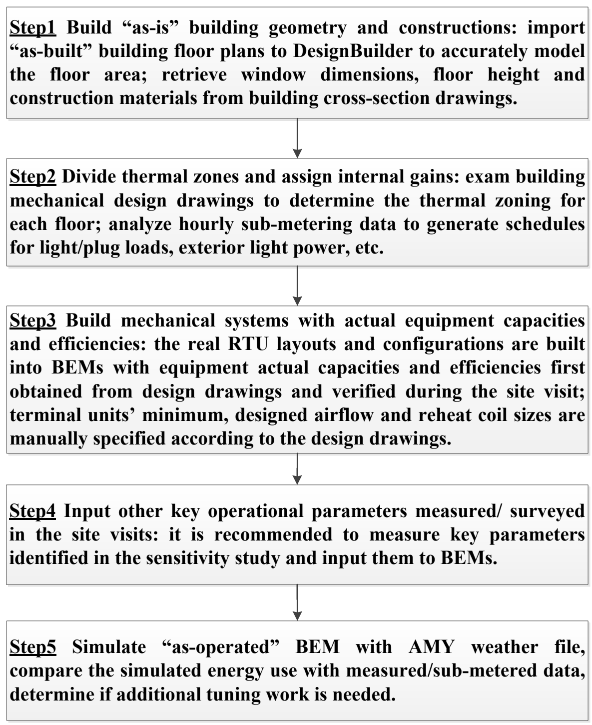


Figure 1: Procedure to build an "as-operated" BEM

## DESCRIPTIONS OF CASE STUDY BUILDINGS

Case study Building I and II are 20 miles apart from each other, owned and operated by the same real estate development company. Building I is a three-story, commercial medium size office building located in Malvern, PA with the gross area of 101,700 $ft^2$. The building was built in 2004 with full-height glass curtain wall systems. Three variable-air-volume (VAV) rooftop units (RTUs) provide conditioned air to all spaces except for a few server rooms which are served by dedicated units. Direct Expansion (DX) unitary systems are used for cooling and electric resistance coils in the ductwork are designed to provide heat to the building. Building perimeter zones are served by series fan powered terminal boxes (FPTBs) with electric reheat coils while the interior spaces are served by conventional VAV terminal boxes (VAVTBs) with electric reheat coils. Most building offices are lit by 2ft by 4ft three T-8 32 Watts fluorescent lamps and the building exterior facades and parking lots are lit by metal halide pole lamps controlled by the BAS. Multiple tenants including bank, institution, dental and information service companies lease the building spaces. Building II, located in Fort Washington, PA, is a smaller three-story office building with gross floor area of 74,140 $ft^2$. Unlike Building I, it has pre-cast masonry panels with partial glass curtain wall system as envelopes. Similar heating, ventilation and air conditioning (HVAC) system types, configurations and exterior/interior lighting systems can be found in this building as in Building I. In contrast, only a single tenant-an engineering firm is identified to lease the building. Figure 2 shows the pictures of buildings. Both were originally designed for a special electric heating rate, thus they were provided with separate meters for electric heating within the general service (GS, mainly includes lighting and receptacle loads) electric wiring from HVAC loads. This leads to the design of two independent electric main distribution panels (MDP) and power meters. Three-year (2008-2010) averaged site EUI for Building I and II is calculated as 73 and 72 kbtu/$ft^2$-yr, respectively.


Figure 2: Building Pictures (left: Building I; right: Building II)

## "AS-OPERATED" BUILDING ENERGY MODELING

"As-operated" BEMs were constructed following the procedure in Figure 1. Figure 3 displays rendered three dimensional (3D) building structures. Both buildings are rectangular shaped, and "as-is" thermal zones are allocated: for more than 120 thermal zones built within Building I and over 60 zones were built for Building II. The designed airflow, minimum primary airflow and fan motor size for each terminal unit were extracted from the building schedules on the drawings or from control documents for input to the models.

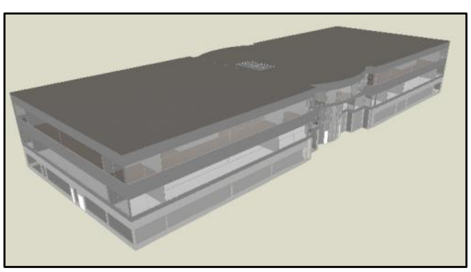
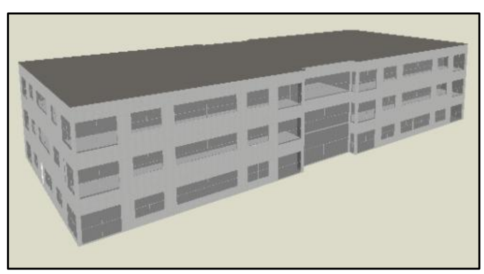

Figure 3: Building I (left) and Building II (right) model rendering

Five steps are followed to analyse sub-metered data: 1). Group hourly GS meter energy data into two day types-weekdays and weekends (including holidays). 2). Examine weekend GS hourly profile to gain exterior lighting power density and schedule. 3).

Estimate the power of IT equipment in server rooms, assuming the base load shown on HVAC meter is consumed by the server room AC equipment. 4). Derive building interior lighting use schedules as shown in Figure 4. 5). Develop the interior receptacle load schedules by subtracting the exterior, interior lighting energy use and constant server loads from GS meter readings, as can be seen from Figure 4. The supply fan schedules are also obtained from the measured HVAC meter energy use. Table 1 lists twenty variables that are most sensitive to the medium size office building annual energy use in Climate Zone 4A, their values and data resources used in both BEMs.

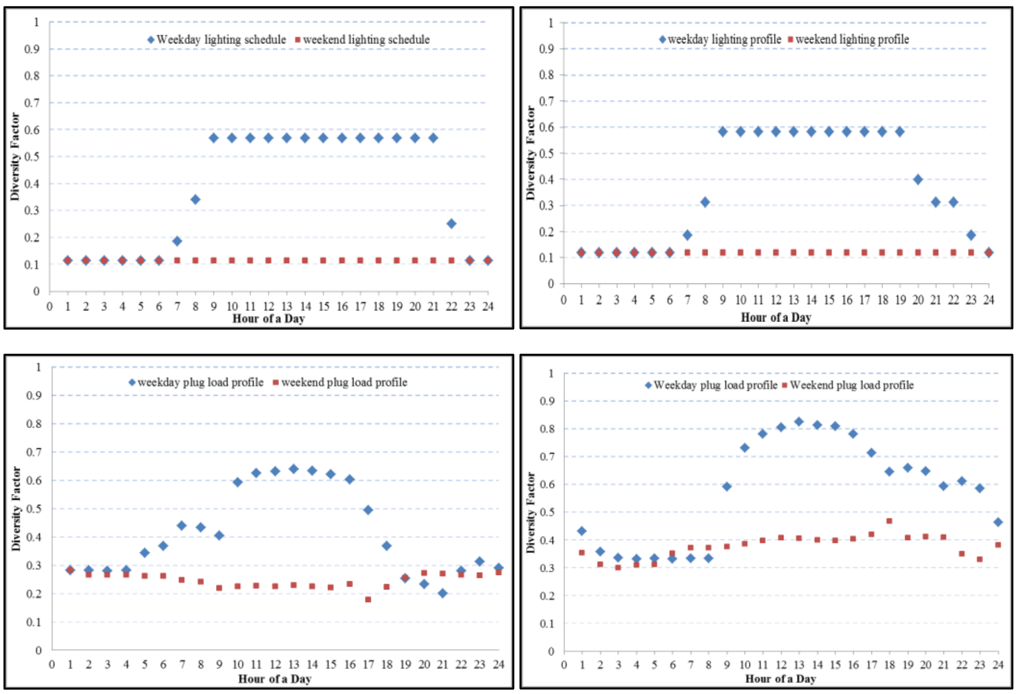


Figure 4: Derived interior lighting (top) and plug load (bottom) schedules (left: Building I; right: Building II).

Table 1: Key inputs for Building I and II energy models

| Key Input Variables | Building I | Building II | Data Source |
|---|---|---|---|
| SEPTTRMH | 72 °F for occupied hours and 60°F for unoccupied hours | 71 °F for occupied hours and 60°F for unoccupied hours | As-Operated (EMCS Screening and Doc.) |
| PLPD | 1 W/ft$^2$ | 1.2 W/ft$^2$ | Educated Guess |
| SEPMINAFLTB | Averaged 0.287 | Averaged 0.162 | As-Designed |
| SCHPL | Shown in Figure 4 | Shown in Figure 4 | Measured (Derived from Sub-Metering Data ) |
| LPDIL | 1.1W/ft$^2$ | 1.4 W/ft$^2$ | As-Designed |
| SEPTTRMC | 75 °F for occupied hours and 85°F for unoccupied hours | 75°F for occupied hours and 85°F for unoccupied hours | As-Operated (EMCS Screening and Doc.) |

| | | | |
|---|---|---|---|
| SCHIL | Shown in Figure 4 | Shown in Figure 4 | Measured (Derived from Sub-Metering Data ) |
| SFCNTRL | RTU fans are on from 6am to 6pm on Mon. Wed. and Fri.; RTU fans are on from 6am to 9:30pm on Tue. Thurs.; Off for other days. | RTU fans are turned on from 6:30am to 6pm in weekdays; Off for the weekends. | Measured (Derived from Sub-Metering Data ) |
| EFFREHEAT | 1 | 1 | Educated Guess |
| RWIN | 2.1 $ft^2$-°F-hr/Btu | 2.5 $ft^2$-°F-hr/Btu | As-Designed |
| LPDEL | 13 KW | 8 KW | Measured (Derived from Sub-Metering Data ) |
| SHGCWIN | 0.36 | 0.172 | As-Designed (Manufacture) |
| COPCOOLLSPD | 3.2 | 3.2 | As-Designed (Manufacture) |
| CAPCOOL | 3*115 Tons | 2*115 Tons | As-Designed |
| SEPTSAT | 55 °F | 55 °F | As-Operated (EMCS Screening and Control Doc.) |
| REXTWALL | 12 $ft^2$-°F-hr/Btu | 14 $ft^2$-°F-hr/Btu | As-Designed |
| INFIL | 0.2 ACH | 0.2 ACH | Educated Guess |
| HEADSF | 6 in. w.g. | 6.5 in. w.g. | As-Designed |
| REXTROOF | 20 $ft^2$-°F-hr/Btu | 15 $ft^2$-°F-hr/Btu | As-Designed |
| SETPTCUTCOOL | N/A | N/A | N/A |

## RESULTS

Actual meteorological year (AMY) hourly weather file for Malvern, PA is used to perform real-time simulations to facilitate a direct comparison to the building sub-metered energy data. The simulated annual (from Feb, 18$^{th}$, 2010 to Feb, 17$^{th}$, 2011) site EUI for Building I is 74.5 kbtu/$ft^2$-yr, while the simulated annual (from Mar, 17$^{th}$, 2010 to Feb, 28$^{th}$, 2011) site EUI for Building II is 70.5 kbtu/$ft^2$-yr.

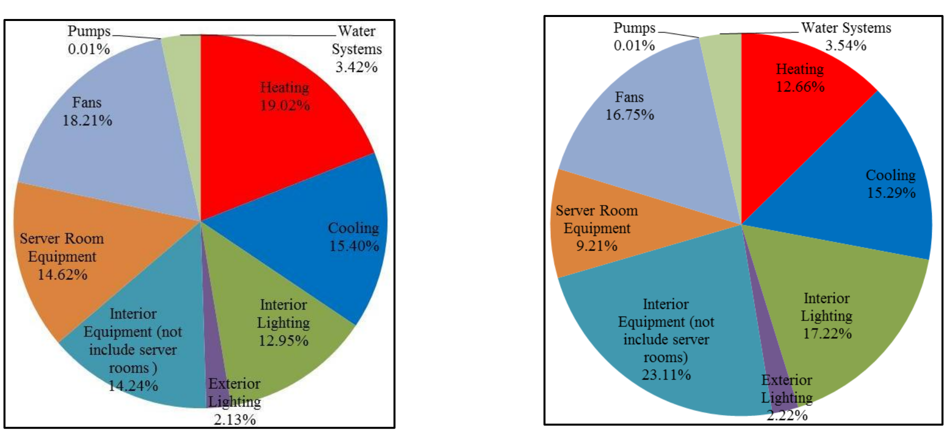


Figure 5: Simulated annul building energy breakdown (left to right: Building I and II).

Figure 5 shows the end-use breakdown for both buildings. Statistical indexes- normalized mean bias error (NMBE, %) and coefficient of variation of the root- mean-square-error (CV (RMSE), %) are calculated using Equation (1) and (2) to demonstrate models compliance with well-accepted, pre-determined criteria- ASHRAE Guideline 14-2002 states that models are declared to be calibrated if they produce MBEs within ±5% and CV (RMSE) within ±15% with monthly data. Table 2 summarizes that the NMBE for both buildings is calculated as 2-3%, and the CV (RMSE) is about 9% for Building I and 6% for Building II.

$$NMBE = \frac{\sum(y_m - y_s)}{(n-1) * \overline{y_m}} \times 100 \qquad \text{Equation (1)}$$

$$CV(RMSE) = \frac{\left[\frac{\sum(y_m - y_s)^2}{(n-p)}\right]^{1/2}}{\overline{y_m}} \times 100 \qquad \text{Equation (2)}$$

Where $y_m$, $y_s$ and $\overline{y_m}$ is the measured, simulated and averaged measured energy use, respectively; n is the number of measured data points; p=1.

Table 2: Building annual simulated energy use and measured energy use.

| Building | Start Date~ End Date | Measured Whole Building Energy Use (KWh) | Simulated Whole Building Energy Use (KWh) | NMBE (%) | CV (RMSE) (%) |
|---|---|---|---|---|---|
| Building I | 2/18/2010 ~2/17/2011 | 2,210,305.0 | 2,247,371.7 | -1.8 | 8.6 |
| Building II | 3/17/2010 ~2/28/2011 | 1,428,658.0 | 1,462,617.0 | -2.6 | 5.9 |

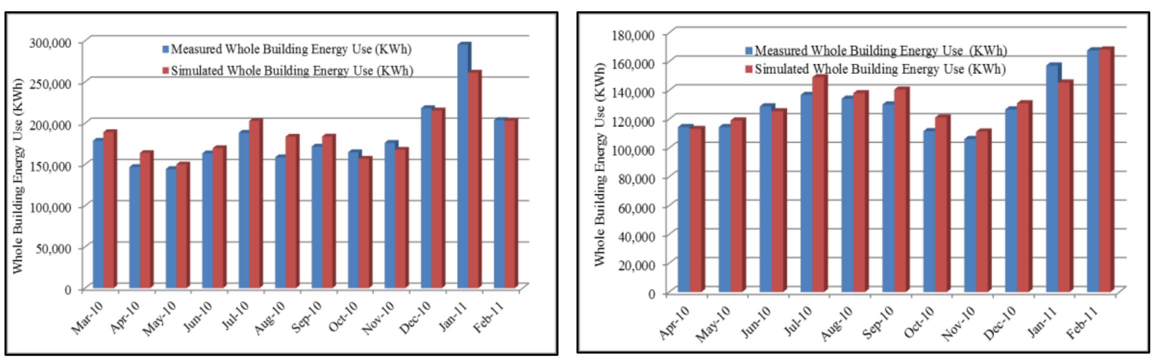


Figure 6: Monthly comparison of simulated and measure building energy use (left: Building I; right: Building II).

Monthly (for each billing period) comparisons are shown in Figure 6. The models predict more accurately in transition seasons (spring and fall), when the minimum heating and cooling is required, with relative error within ±5%. It is mainly because internal lighting and receptacle loads dominate in these months, and their usage patterns are monitored, analysed and then incorporated into the models. The models' predictions can be up to

10-15% off compared to the measured building energy use in the heating or cooling months. The simulation tends to underestimate building energy use in winter months and overestimate it in the cooling season, which suggests potential systematic errors may exist in other inputs that haven't been verified in this study, such as field measured weather conditions. The simulated hourly energy uses for the different end uses are properly aggregated to mimic the GS and HVAC meters according to the sub-metering plans and used to compare with the actual sub-metered data, as shown in Figure 7.

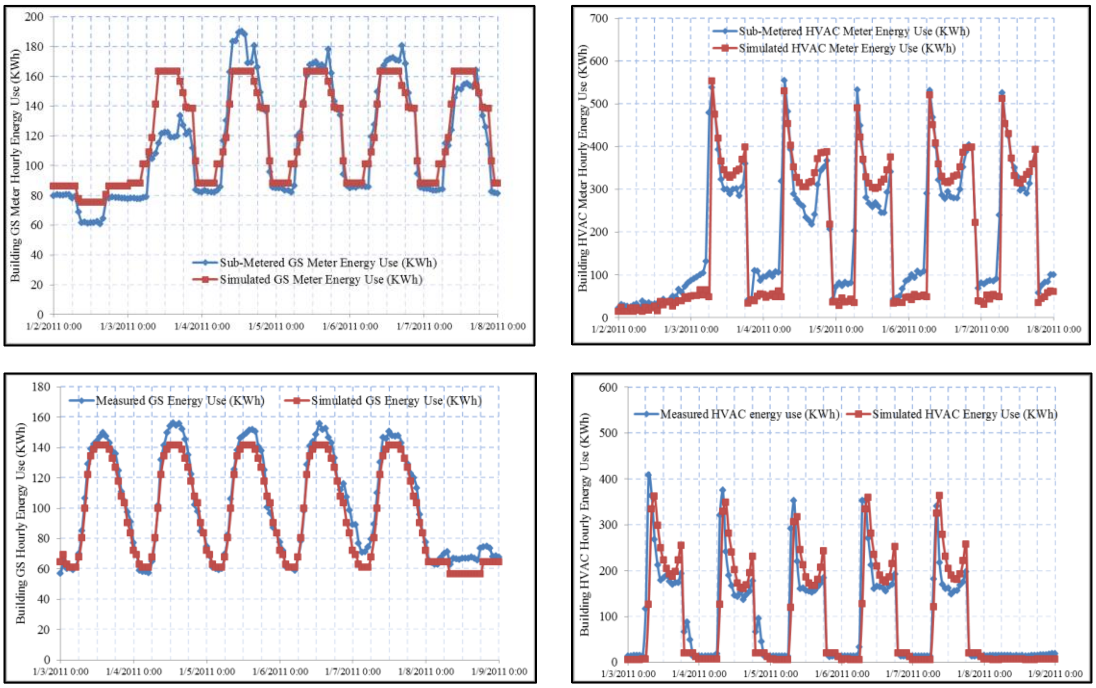


Figure 7: Building I (top) and Building II (bottom) simulated and measured hourly GS meter (left) energy use comparison and HVAC meter (right) comparison.

## CONCULSIONS AND FUTURE STUDY

This study demonstrates the process, tasks and entire workflow required to establish accurate "as-operated" BEMs for two existing medium size office buildings. A pre-determined, prioritized, key parameter list created through SA to a similar sized DOE-reference building guides the data collection process. Besides the building assets information, "as-is" building floor plans, envelopes, thermal zones and HVAC equipment sizes, etc. are required to be captured in the BEMs. Inverse analysis techniques are developed to analyze sub-metered building lighting and plug system energy use data to generate inputs for the models. As a result, the actual usage patterns of several end uses- exterior/interior lighting, plug load and constant server loads- are thoroughly studied and "inversely" included in the models. The fact that the calculated NMBE and CV (RMSE) lies within the threshold defined by ASHRAE Guideline 14, indicates the models are well calibrated. The hourly energy use comparison also illustrates that the models are able to capture the dynamics of the building thermal loads while predicting the associated end-use energy use requirements, necessary information for participating in demand response incentive programs available through local utilities.

The interior lighting and receptacle loads (including constant IT equipment in server rooms) in both studied office buildings consume a large fraction, about 50%, of annual building energy. They are also the main contributors of the office building internal heat gains. Considering these loads are significantly impacted by the occupants' schedules, work characteristics and behaviors (Delgoshaei, 2013), a "forward" approach-first principal based modeling would not be able to accurately predict the usage and patterns. As a result, in most simulation programs, these end uses are heavily determined by user-defined schedules. For the two case study buildings presented in this paper, the derived lighting and plug load schedules deviate substantially from default schedules generally specified. Thus it is recommended to at least sub-meter schedule-dominated loads to further isolate them from the whole building energy use in similar medium office buildings. Moreover, by instrumenting other vital operational parameters identified in the SA, the BEMs for medium size office buildings can be well tuned to the current operation conditions, not only by matching the whole building energy use, but also with the correct end use breakdown. This capability delineates certain constraints to the calculated system energy savings when the BEMs are later used to evaluate ECMs. AMY weather files are directly used in both building simulations, and given the fact the onsite outdoor air temperatures and solar fluxes at a specific building site usually differ from weather station, the errors caused by these factors are not assessed in this study and could be further investigated in a future study.

## ACKNOWLEDGEMENT

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# HIGH DYNAMIC RANGE PHOTOGRAMMETRY FOR LIGHT AND GEOMETRY MEASUREMENT

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When people perceive the world, their eyes simultaneously acquire light and geometry to constitute an image that is interpreted in the brain as vision. The real-time synchronous measurement of light (in photometry) and geometry is desired in many scientific and industrial applications related to visual perception. Conventionally, meters and tools have been used for measuring light and geometry. Digital cameras can also measure light or geometry, such as recently validated high dynamic range (HDR) photography for luminance mapping a static scenario, and metric-camera-aided photogrammetry for measuring geometry. Unfortunately, existing technologies cannot measure light and geometry simultaneously. The separated measurements increase the labor, slow the data collection, and cause difficulties in follow-up data alignment. To break through these limitations, HDR photogrammetry was recently developed for synchronous acquisition of luminance of targets across a scene and their three dimensional coordinates XYZ in the field. The HDR photogrammetry deploys a single consumer grade digital camera fitted with a standard, wide-angle, or fisheye lens, mounted on a portable measurement platform. The HDR photogrammetry was validated in a laboratory experiment. The average errors of 1.8% – 6.2% for luminance mapping seven grey checkers and 12.9 – 24.3 mm for measuring their XYZ coordinates are deemed acceptable in practice. The HDR photogrammetry would supplement light and geometry measurement and stimulate many applications. This paper introduces several indoor and outdoor applications of the HDR photogrammetry, using a Canon EOS Rebel T2i fitted with a 10 mm Sigma EX DC HSM fisheye lens as the main test rig, for measuring light and geometry simultaneously.

Keywords Camera, high dynamic range, geometry, light, photogrammetry, synchronous measurement

## 1. INTRODUCTION

Motivated by the human vision, the synchronous measurement of light (in photometry) and geometry is desired in many scientific and industrial applications related to visual perception. In architectural engineering, for example, the synchronous measurement of light and geometry could enable the acquisition of real common non-uniform lighting conditions, thereby benefiting lighting quality assessment, discomfort glare evaluation, daylight harvesting, etc. However, we are not there yet.

Conventionally, for measuring light, meters like Minolta LS-100, T-10, and CL-200A are popular. Meters with calibration are reliable and accurate, but the point-by-point measurement process is tedious with low resolution (number of measured points per surface area). As a result, meters are incapable of measuring common non-uniform lighting in practice. For measuring geometry, rulers, tapes, wheel rolls, calipers, micrometers, laser distance meters, and laser rangefinders can measure distances, while protractors and magnetic angle locators are used for measuring angles. Such geometry measurements are also tedious, point by point.

Digital cameras have also been used for measuring light (in photometry) or geometry. High dynamic range (HDR) photography using consumer grade digital cameras has recently been validated for luminance mapping a static scene at pixel level (Cai & Chung, 2011; Inanici, 2006). Low dynamic range (LDR) photographs are sequentially exposed to cover the high dynamic range of light, due to the limited recording capability of existing imaging sensors (Nayar & Branzoi, 2003). An HDR image is then fused from an appropriate exposure range of those LDR photographs using a free software program (e.g., Radiance, photosphere, HDRgen). The HDR photography has an error ≤ 5% for measuring grey surfaces, and approximately 10% for color surfaces (Cai & Chung, 2011; Inanici, 2006). For measuring geometry, metric-camera-aided photogrammetry has been used in architecture, archaeology and land survey, etc. Example metric cameras include Zeiss TMK6, SMK40, SMK120, Optech KCM HD, KCM 11, KCM 39, MS-4100, and a recently released UltraCam-Lp. With calibration, metric cameras have constant interior orientation, precisely known internal geometries and very low lens distortions, ideal for geometry measurement. However, metric cameras have fixed aperture sizes and focal lengths of the lens as well as limited variation of shutter speeds. They are also bulky and heavy (e.g., 450×450×800 $mm^3$ and 55 kg for UltraCam-Lp[9]). Therefore, metric cameras are inappropriate for portable light measurement (Maas & Hampel, 2006; El-Hakim et al., 2003).

## 2. RESEARCH GAP AND PROBLEMS

The existing light and geometry measurements are separated. The separated measurements increase the labor, slow the data collection, and cause difficulties in follow-up data alignment due to displaced measuring points and inconsistent measuring resolutions. These problems have hindered the development of the lighting profession, which relies heavily on the lighting measurement technology (the artificial light sources as well) (Cai & Chung, 2010). One cause is the inability to measure common non-uniform light distributions. The other cause is the difficulty in measuring geometries (e.g., sizes, solid angles, etc.) of every single tiny luminous element across a large surface.

Digital cameras have great potentials to bridge this research gap. Digital cameras have three advantages over conventional meters and tools. First, digital cameras can record an entire scene within a short exposure time (1-2 minutes). Second, digital cameras make non-contact measurements (Cornolly & Leung, 1995). Third, each photographic image can acquire millions of values at pixel level, depending on the pixel resolution of the camera's imaging sensor. In addition, the HDR photography has low entry barriers — affordable hardware (i.e., cameras, lenses, computers), free software (i.e., Radiance, Photosphere HDRgen, etc.), and easy computer-aided manipulation. However, the HDR photography used for luminance mapping cannot measure geometry. In addition, most wide-angle and fisheye lenses have lens distortions, which the HDR photography cannot correct. These two limitations need to be overcome for synchronous measurement of light and geometry.

## 3. THE HDR PHOTOGRAMMETRIC MEASUREMENT

The author recently published a paper on the HDR photogrammetry for synchronous acquisition of luminance of any target points across a scene and their right-handed Cartesian coordinates XYZ in the field (Cai, 2012). The HDR photogrammetry deploys a single consumer grade digital camera fitted with a standard, wide-angle, or fisheye lens, mounted on a portable measurement platform. This paper introduces a Canon EOS Rebel T2i fitted with a 10 mm Sigma EX DC HSM fisheye lens as the main test rig.

Here is a brief introduction to the HDR photogrammetric measurement, with aid of the HDR photogrammetry. As shown in Figure 1, the Canon camera T2i is mounted at the focal point, with yaw, pitch, and roll angles related to the world coordinates XYZ, following the right hand rule. The camera is used to take multiple low dynamic range (LDR) photographs of the test scene, which are then generated into an HDR image, containing light and geometry information at pixel level. The HDR image plane is located on the image sensor of the camera, with pixel coordinates xz in lowercase. Any single target plane in two dimensions, on which targets are randomly distributed, also has yaw, pitch, and roll angles in light of the world coordinates XYZ, as shown in Figure 1. A target P and a reference point $P_i$ are both located on the target plane in blue. The target plane has yaw, pitch and roll angles along the Z, X and Y axis, thus, out of perspective of Figure 1. The position of reference point $P_i$ in world coordinates is actually measured in the field. Minimum three, ideally four reference points are needed for each target plane.

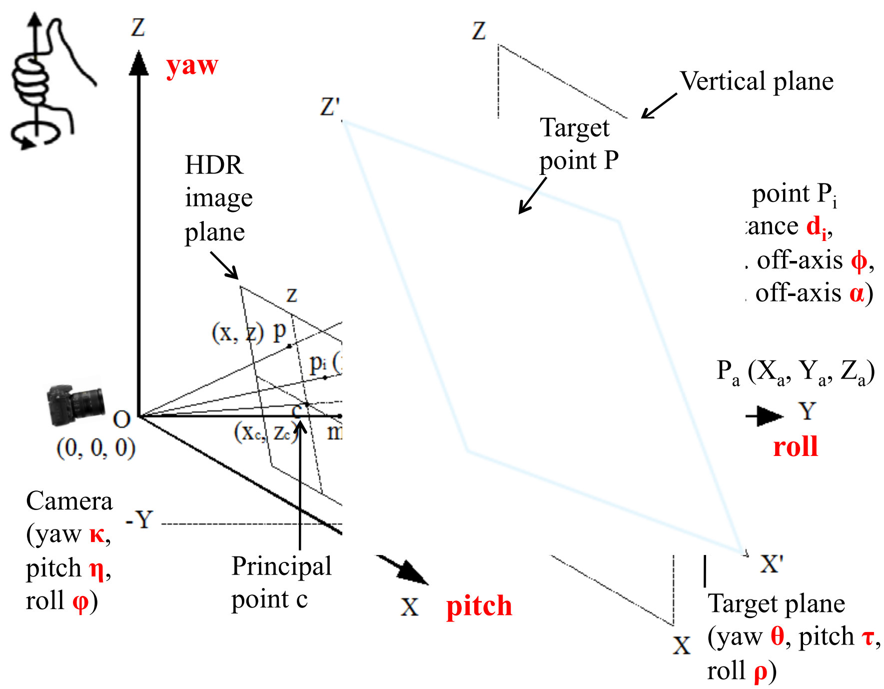


**Figure 1** Photogrammetric coordinates of the HDR photogrammetry

The location of the target P in world coordinates can then be calculated from its pixel location (x, z) on the HDR image, aided by the reference point $P_i$, by using some photogrammetric transforming equations. At the same time, the luminance value $L$ of any pixel can also be obtained from the HDR image generated using the HDR photogrammetry. Accordingly, with known luminance and geometry, it is possible to evaluate lighting and geometry of the test scene at pixel level, as well as other combined parameters, such as discomfort glare and legibility.

**3.1 Measurement procedure**

***Step 1: Field preparation.*** First, find a proper location to mount the camera. The camera location shall have the best field of view (FOV) of the entire scene, for the camera to capture all target points. Next, identify some reference points at four corners of each target plane. Further, mount an X-Rite 18% gray checker or a Macbeth color checker on a tripod close to the camera shooting line for photometric calibration.

***Step 2: Platform setup and leveling.*** A 3D angular measurement tripod head is then mounted on a heavy-duty flat head tripod (e.g., a CST/Berger tripod) and leveled. The tripod head has an adjustable base with three screws under the base for micro-adjustment to ensure the platform is truly horizontal at its initial position. The tripod has three angular dials on the base, front and side to record the aiming yaw, pitch and roll angle.

***Step 3: Determining the XYZ coordinates and directions.*** Either the world coordinate system (WCS) or the user coordinate system (UCS) is used. The WCS has fixed coordinates —X (east), Y (north), Z (up). The UCS adopts arbitrary XYZ in relation to the physical characteristics of a scene (e.g., walls). The WCS is appropriate for exterior measurements, while the UCS is preferred for interior spaces. In either case, the origin point O overlapped at the optical center (0, 0, 0) of the camera. The next procedure is to determine the initial orientation of XYZ coordinates ($\kappa_{XYZ}, \eta_{XYZ}, \varphi_{XYZ}$), using a compass.

***Step 4: HDR photographing.*** A camera aiming point was used for photographing. The Canon camera T2i was manually focused on the aiming point/target, making all other interested targets in focus across the entire roadway environment. A color meter Minolta CL-200A was used to measure the CCT and illuminance at the camera lens. The CCT was used for white balancing of photographing. The vertical illuminance value at the lens was used for control. The camera was then remotely controlled by a laptop to take 18 LDR images, which was later generated into a raw HDR image. During the photographing, luminance of the X-Rite 18% gray checker was measured using a luminance meter Minolta LS-100 for photometric calibrations of raw HDR images.

***Step 5: Field measurements and calibration.*** Camera's initial aiming angles ($\kappa_0$, $\eta_0$, $\varphi_0$) were recorded from the three angular dials of the 3D angular measurement tripod head. The actual aiming angles were calculated as $\kappa = \kappa_0 - \kappa_{XYZ}, \eta = \eta_0 - \eta_{XYZ}, \varphi = \varphi_0 - \varphi_{XYZ}$. The camera was then dismounted and replaced with a laser distance meter (for close and middle range) or a laser rangefinder (for wide range) for measuring the distance $d_i$ of a reference point $P_i$. The aiming angles of $P_i\,(\phi_{i,\alpha}, \alpha_{i,\alpha})$ were recorded on the side and base angular dials. Note that during the replacement of the camera with the laser distance meter or the rangefinder, the aiming direction may change. To calibrate this error, the laser distance meter or the rangefinder was re-aimed to the same target point of the camera. The new aiming direction $(\kappa_{m0}, \eta_{m0}, \varphi_{m0})$ was recorded from the three angular dials. The offsets of the aiming angles are calculated using Equation (1). The off-axis angles were then calculated using Equation (2).

$$\begin{cases} \Delta\kappa = \kappa_{m0} - \kappa_0 \\ \Delta\eta = \eta_{m0} - \eta_0 \end{cases} \quad (1)$$

$$\begin{cases} \phi_i = \phi_{i,\alpha} - \kappa_{XYZ} - \Delta\kappa \\ \alpha_i = \alpha_{i,\alpha} - \eta_{XYZ} - \Delta\eta \end{cases} \quad (2)$$

### 3.2 Data treatment

***Step 1: Generation of raw HDR images.*** Raw HDR images were then generated using Photosphere or Radiance from those LDR photographs (Cai & Chung, 2011; Inanici, 2006). Before that, the LDR photographs need treatments to filter any unwanted voltage bias, dark current and conductive noise, and fixed pattern noise (Cai & Chung, 2011, Chuang & Cai, 2010).

***Step 2: Calibrations of the raw HDR images.*** The raw HDR images were then calibrated in Radiance, including, in order, (a) vignetting effect correction, and (b) photometric calibration.

***Step 3: Data retrieval from calibrated HDR images.*** Of every single pixel, the luminance and pixel location were extracted from the calibrated HDR images in Radiance. The distorted geometric coordinate $P_d(x_d, z_d)$ was then derived.

***Step 4: Correction of the lens distortion.*** Of each pixel, the distorted coordinates on the image plane were corrected. The distorted pixel coordinate $P_d(x_d, z_d)$ was corrected using Equations (3) – (6) (Cai, 2012). All the parameters in the model were known from calibrations in the laboratory in advance (Cai, 2012).

$$\gamma_{S,S'} = \frac{S-f}{S'-f} \times \frac{S'}{S} \quad (3)$$

$$\alpha_{S'} = \frac{S_2-S'}{S_2-S_1} \times \frac{S_1-f}{S'-f} \quad (4)$$

$$\begin{cases} k_{1,S'} = \alpha_{S'} \cdot k_{1,S1} + (1-\alpha_{S'}) \cdot k_{1,S2} \\ k_{2,S'} = \alpha_{S'} \cdot k_{2,S1} + (1-\alpha_{S'}) \cdot k_{2,S2} \\ k_{3,S'} = \alpha_{S'} \cdot k_{3,S1} + (1-\alpha_{S'}) \cdot k_{3,S2} \end{cases} \quad (5)$$

$$\begin{cases} x_u = x_{d,S} + x_{d,S} \cdot (\gamma_{S,S'}^2 \cdot k_{1,S'} \cdot r_{d,S}^2 + \gamma_{S,S'}^4 \cdot k_{2,S'} \cdot r_{d,S}^4 + \gamma_{S,S'}^6 \cdot k_{3,S'} \cdot r_{d,S}^6 + \cdots) \\ z_u = z_{d,S} + z_{d,S} \cdot (\gamma_{S,S'}^2 \cdot k_{1,S'} \cdot r_{d,S}^2 + \gamma_{S,S'}^4 \cdot k_{2,S'} \cdot r_{d,S}^4 + \gamma_{S,S'}^6 \cdot k_{3,S'} \cdot r_{d,S}^6 + \cdots) \end{cases} \quad (6)$$

***Step 5: Photogrammetric transformation and calibration.*** The undistorted coordinates $P_u(x_u, z_u)$ on the image plane were then transformed to WCS or UCS coordinates in the field (Cai, 2012). The raw data was further calibrated. A Matlab program was developed to improve the efficiency of this process. First, four reference points $P_i$ ($X_i$, $Y_i$, $Z_i$) were calculated using Equation (7). Equations (8) was used to calculate the vector (A, B, C) of the target plane using the coordinates of three reference points. In particular, if target points were located on a horizontal plane, such as the roadway, the vector (A, B, C) can be simplified using Equation (9), where $\overline{Z} = (Z_1 + Z_2 + Z_3 + Z_4)/4$. Also, for horizontal planes only, the yaw, pitch and roll angles of target planes and perpendicular distance S' of the target plane to focal point O, were calculated using Equations (10) and (11). Equations (12) and (13) were used to convert the WCS coordinates XYZ to local coordinates X'Y'Z'. To save space, some symbols are simplified. $\cos(\rho) = c\rho, \sin(\rho) = s\rho, \cos(\theta) = c\theta, \sin(\theta) = s\theta, \cos(\tau) = c\tau, \sin(\tau) = s\tau.$ The next step was to calculate the local coordinates X'Y'Z' of the target point *P*, using Equations (14) and (15), from the undistorted geometric coordinates $P_u(x_u, z_u)$. Then the local X'Y'Z' coordinates were converted back to the WCS coordinates P (X, Y, Z), using Equation (16). The last step was the photogrammetric calibration using the coordinates of four reference points. Their average geometric deviation $(\Delta\bar{X}, \Delta\bar{Y}, \Delta\bar{Z})$ was calculated using Equation (17). *P* (X, Y, Z) is further calibrated by the offset $(\Delta\bar{X}, \Delta\bar{Y}, \Delta\bar{Z})$ using Equation (18).

$$\begin{pmatrix} X_i \\ Y_i \\ Z_i \end{pmatrix} = \begin{pmatrix} d_i cos\alpha_i \sin(-\phi_i) \\ d_i cos\alpha_i \cos(-\phi_i) \\ d_i sin\alpha_i \end{pmatrix} \tag{7}$$

$$\begin{pmatrix} A \\ B \\ C \end{pmatrix} = \begin{pmatrix} \frac{Y_1(Z_2-Z_3)+Y_2(Z_3-Z_1)+Y_3(Z_1-Z_2)}{X_1(Y_2Z_3-Y_3Z_2)+X_2(Y_3Z_1-Y_1Z_3)+X_3(Y_1Z_2-Y_2Z_1)} \\ \frac{Z_1(X_2-X_3)+Z_2(X_3-X_1)+Z_3(X_1-X_2)}{X_1(Y_2Z_3-Y_3Z_2)+X_2(Y_3Z_1-Y_1Z_3)+X_3(Y_1Z_2-Y_2Z_1)} \\ \frac{X_1(Y_2-Y_3)+X_2(Y_3-Y_1)+X_3(Y_1-Y_2)}{X_1(Y_2Z_3-Y_3Z_2)+X_2(Y_3Z_1-Y_1Z_3)+X_3(Y_1Z_2-Y_2Z_1)} \end{pmatrix} \tag{8}$$

$$\begin{pmatrix} A \\ B \\ C \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \\ \frac{X_1(Y_2-Y_3)+X_2(Y_3-Y_1)+X_3(Y_1-Y_2)}{X_1(Y_2\overline{Z}-Y_3\overline{Z})+X_2(Y_3\overline{Z}-Y_1\overline{Z})+X_3(Y_1\overline{Z}-Y_2\overline{Z})} \end{pmatrix} \tag{9}$$

$$\begin{pmatrix} \theta \\ \tau \\ \rho \end{pmatrix} = \begin{pmatrix} 0 \\ 90 \\ 0 \end{pmatrix} \tag{10}$$

$$S' = \left|\frac{1}{C}\right| \tag{11}$$

$$\begin{pmatrix} X_i' \\ Y_i' \\ Z_i' \end{pmatrix} = \begin{pmatrix} r_{11}' & r_{12}' & r_{13}' \\ r_{21}' & r_{22}' & r_{23}' \\ r_{31}' & r_{32}' & r_{33}' \end{pmatrix}^{-1} \begin{pmatrix} X_i \\ Y_i \\ Z_i \end{pmatrix} \tag{12}$$

$$\begin{pmatrix} r_{11}' & r_{12}' & r_{13}' \\ r_{21}' & r_{22}' & r_{23}' \\ r_{31}' & r_{32}' & r_{33}' \end{pmatrix} = \begin{pmatrix} c\rho c\theta & -c\rho s\theta & s\rho \\ c\tau s\theta + s\tau s\rho c\theta & c\tau c\theta - s\tau s\rho s\theta & -s\tau c\rho \\ s\tau s\theta - c\tau s\rho c\theta & s\tau c\theta + c\tau s\rho s\theta & c\tau c\rho \end{pmatrix} \tag{13}$$

$$\begin{cases} X' = X_0' + (Y' - Y_0')\dfrac{R_{11}x_u + R_{12}f + R_{13}z_u}{R_{21}x_u + R_{22}f + R_{23}z_u} \\ Z' = Z_0' + (Y' - Y_0')\dfrac{R_{31}x_u + R_{32}f + R_{33}z_u}{R_{21}x_u + R_{22}f + R_{23}z_u} \\ Y' = Y_i' \end{cases} \tag{14}$$

$$\begin{pmatrix} R_{11} & R_{12} & R_{13} \\ R_{21} & R_{22} & R_{23} \\ R_{31} & R_{32} & R_{33} \end{pmatrix} = \begin{pmatrix} c(\varphi-\rho)c(\kappa-\theta) & -c(\varphi-\rho)s(\kappa-\theta) & s(\varphi-\rho) \\ \begin{array}{l} c(\eta-\tau)s(\kappa-\theta)+ \\ s(\eta-\tau)s(\varphi-\rho)c(\kappa-\theta) \end{array} & \begin{array}{l} c(\eta-\tau)c(\kappa-\theta)- \\ s(\eta-\tau)s(\varphi-\rho)s(\kappa-\theta) \end{array} & -s(\eta-\tau)c(\varphi-\rho) \\ \begin{array}{l} s(\eta-\tau)s(\kappa-\theta)- \\ c(\eta-\tau)s(\varphi-\rho)c(\kappa-\theta) \end{array} & \begin{array}{l} s(\eta-\tau)c(\kappa-\theta)+ \\ c(\eta-\tau)s(\varphi-\rho)s(\kappa-\theta) \end{array} & c(\eta-\tau)c(\varphi-\rho) \end{pmatrix} \quad (15)$$

$$\begin{pmatrix} X \\ Y \\ Z \end{pmatrix} = \begin{pmatrix} r'_{11} & r'_{12} & r'_{13} \\ r'_{21} & r'_{22} & r'_{23} \\ r'_{31} & r'_{32} & r'_{33} \end{pmatrix} \begin{pmatrix} X' \\ Y' \\ Z' \end{pmatrix} \quad (16)$$

$$\begin{cases} \Delta\bar{X} = (\Delta X_1 + \Delta X_2 + \Delta X_3 + \Delta X_4)/4 \\ \Delta\bar{Y} = (\Delta Y_1 + \Delta Y_2 + \Delta Y_3 + \Delta Y_4)/4 \\ \Delta\bar{Z} = (\Delta Z_1 + \Delta Z_2 + \Delta Z_3 + \Delta Z_4)/4 \end{cases} \quad (17)$$

$$\begin{cases} X_{cali} = X - \Delta\bar{X} \\ Y_{cali} = Y - \Delta\bar{Y} \\ Z_{cali} = Z - \Delta\bar{Z} \end{cases} \quad (18)$$

***Step 6: Collection of synchronous data.*** Of every single pixel, its luminance *L* and 3D coordinates P ($X_{cali}$, $Y_{cali}$, $Z_{cali}$) were collected for further data treatments.

## 4. LABORATORY VALIDATION

An experiment was conducted in the windowless Bob Foley illumination laboratory (232 Art & Design building) to test the HDR photogrammetry. The laboratory is 5.8 m wide, 7.9 m long, and 2.7 m high, under stable fluorescent lighting. Figure 2(a) shows the experiment setup. Seven target planes at one corner include the whiteboard, three walls, a desktop, an oblique computer screen, and a ceiling tile. Orientations of these target planes were measured in the field. On each target plane, an X-Rite grey checker was mounted at the center as the target, while four reference points at four corners were labeled using colored dots. All four reference points of each target plane were measured in the field for their locations, to determine the orientation of the target plane, or be used as the reference point for photogrammetric transformation. Figure 2 shows the scene photographed using the Canon Rebel T2i fitted with the Sigma 10 mm fisheye lens. The aperture size of f/5.0 was used in this study based on previous studies for optimized settings (Cai & Chung, 2011; Chuang & Cai, 2010). The camera was manually focused on the third patch (neutral 6.5) of a Macbeth color checker removed later for photographing the scene without obstruction. The calibrated HDR images are shown in Figure 2 (b).

The HDR photogrammetry was validated in this well-controlled laboratory experiment for synchronous acquisition of luminance values and XYZ coordinates of any targets in close- and middle-range applications. In the laboratory, the perpendicular distance of the farthest target plane to the camera is 8.14 m. The average errors of 1.8% – 6.2% for luminance mapping seven grey checkers and 12.9 – 24.3 mm for measuring their XYZ coordinates are deemed acceptable in practice.

(a)

(b)

**Figure 2** The HDR photogrammetric measurement in the windowless Bob Foley Illumination Laboratory

# 5. APPLICATION FOR ROADWAY ENVIRONMENT MEASUREMENT

The HDR photogrammetry was also used for off-road and non-contact measurement of two roadway environments on the campus of the University of Kansas (KU), as shown in Figure 3. Experiment A was conducted on a straight section of Jayhawk Boulevard, which goes through the KU campus. On both sides of this road, there are school buildings and multiple roadside objects like trees, light poles, traffic signs, statues, newspaper booth, etc. Experiment B was conducted at a roundabout at the end of the Jayhawk Boulevard. This roundabout has three approaches, with asymmetrical non-straight geometry. These complicated geometric environments are ideal to show the capability of the HDR photogrammetry for measuring roadway environment.

This study also used the Canon EOS Rebel T2i digital Camera fitted with a Sigma EX DC HSM 10mm fisheye lens. Again, the aperture size of f/5.0 was used. Figure 3 (A-1) (B-1) shows the HDR photogrammetric measurement platform used in both scenarios. In both scenarios, HDR images were generated under four weather conditions: clear sky in the daytime (Figure 3 (A-2) (B-2)), clear sky at nighttime (Figure 3 (A-3) (B-3)), cloudy sky in the daytime (Figure 3 (A-4) (B-4)), and rainy night (Figure 3 (A-5) (B-5)). At each scenario, the HDR images capture both light and geometry data. Daytime HDR images under clear sky are very useful to measure the geometry of the roadway environment. Nighttime HDR images are very useful for detection and evaluation of glare, sky glow and light trespass of roadway lighting. HDR images generated in cloudy days and rainy days help quickly evaluate lighting condition under various weather conditions. A total of 24 points were measured on the Jayhawk Blvd, while totally 21 points were measured at the Roundabout. Some points on the road surface were used as reference points for data treatment, other points as target to validate the new method for geometry measurement.

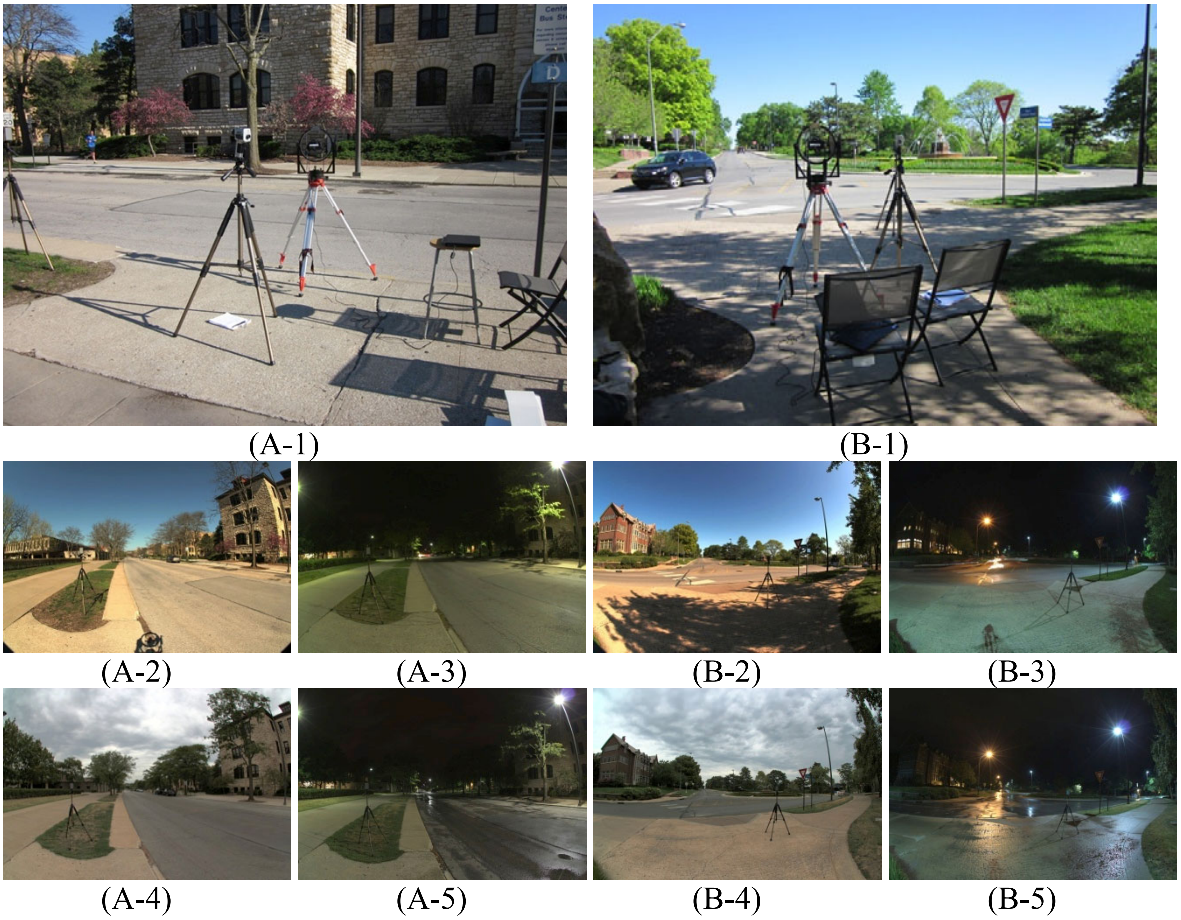


**Figure 3** The HDR photogrammetric measurement on the Jayhawk Boulevard (experiment A) and the Roundabout (B) under four weather conditions: clear sky in the daytime (Figure 3 (A-2) (B-2)), clear sky at nighttime (Figure 3 (A-3) (B-3)), cloudy sky in the daytime (Figure 3 (A-4) (B-4)), and rainy night (Figure 3 (A-5) (B-5))

It was found that the current HDR photogrammetric measurement had wide range of errors for outdoor geometry measurement. For measuring the long Jayhawk Blvd., the errors varied a lot with the measuring distance, from 0.0% to 156.7%. For measuring the closer roundabout, the margin of errors was from 0.0% to 137.5%, but smaller than that of Jayhawk Blvd. The average errors of measured XYZ coordinates of roadway marks were 25.2%, 22.7%, and 22.4% for 24 points on Jayhawk Blvd, and 16.2%, 12.1%, 9.3% for 22 points on the roundabout. Generally, target points that were farther from the camera had larger measuring errors. The largest errors were contributed by the limitations of current HDR photogrammetric measurement equipment. For example, the 3D angular measurement tripod head has a precision of 0.1°, which may be insufficient to measure targets that are very far from the camera, due to the high sensitivity of angles in photogrammetric transformation. In addition, the Rangefinder has an error of ± 1 m, which also contributes to the large errors of far range targets. On the other hand, the accuracy of the HDR photogrammetric techniques for luminance mapping of an entire scene has been proven acceptable by Cai and Chung (2011) and Inanici (2006), thus, not tested in this study.

## 6. CONCLUSIONS AND DISCUSSION

Capturing synchronous light and geometry data with aid of the HDR photogrammetry could largely speed up the indoor and outdoor environment measurement. The camera-aided HDR photogrammetric measurement is rapid, non-contact, and non-destructive, thus, is safer (e.g., off the road) and more efficient (e.g., massive light and geometry data acquisition within 1-2 minutes) than the conventional meters and tools. In addition, the HDR photogrammetric measurement can measure both horizontal & straight planes and oblique & non-straight planes, therefore, is more useful than the conventional ways of geometry measurement. It was very useful for the HDR photogrammetric measurement to capture the spatial and temporal light distributions across the entire scenario. Nonetheless, current technologies of the HDR photogrammetry for measuring wide-range outdoor environments still need improvements of the measurement accuracy. The data treatment is also laborious. A Matlab program is currently under development to aid the photogrammetric transformation and calibrations. Other limitations that need to be tackled in further studies include (a) HDR photogrammetry is applicable for flat planes only, not for curved or 3D surfaces; (b) consumer grade cameras and lenses may have larger errors, due to noise of cameras and decentering distortions of the lens; (c) the calibrations of cameras and lenses are laborious; and (d) variable optical structures of the camera and optical meters, which contribute to differentials in aiming angles that must be compensated in a more accurate way.

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# OFFICE WORKER RESPONSE TO FLUORESCENT LAMPS OF DIFFERENT CCT AND LUMEN OUTPUT

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## Abstract

This paper describes a field study concerning the effects of correlated color temperature (CCT) and lumen output of fluorescent lighting on office workers' perceptions and visual comfort. Four luminous conditions were created and organized as a two by two factorial design, comprising two levels of CCT (that is, 3500 and 5000 K) and lumen output (that is, 2330 and $\approx$ 3000 lm). Participants experienced a baseline condition followed by the four treatment conditions and then returned to the baseline condition; each treatment lasted two weeks. Twenty-six participants adapted to the luminous conditions in the first week of each treatment period. In the second week they completed brief assessment surveys three times daily using smart phones. Participants completed a more comprehensive survey on the last day of each treatment period.

CCT was found to be a significant factor affecting perceptions of brightness, visual comfort, and satisfaction of color temperature. There were interaction effects between CCT and lumen output and between CCT and the presence or absence of a window. The luminous conditions with higher CCT (that is, visually cooler) or higher lumen output were rated to be brighter than those with lower CCT (that is, visually warmer) or lower lumen output. Participants judged the luminous condition with both higher CCT and higher lumen output as being too bright. CCT was the only statistically significant factor for perceived visual comfort and the satisfaction of color temperature. The luminous conditions at 5000 K were regarded as less comfortable than those at 3500 K. 5000 K was judged to be too cool when the higher lumen output lamps were in place. For the participants with daylight in their office, 5000 K was especially judged to be too cool.

**Keywords:** Brightness, Correlated Color Temperature (CCT), Fluorescent Lamp, Lumen Output, Visual Comfort

# 1. INTRODUCTION

In 2010, about 41% of primary energy was consumed by residential and commercial buildings in the United States and lighting accounts for about 10% [DOE 2012a, 2012b]. With the development of lighting technology and the growth of knowledge about human's perception, it is expected that lighting has great potential for energy saving.

The Department of Energy (DOE) is advocating adoption of "spectral enhanced lighting" (SEL), based on the belief that the human visual system responds to increases in color temperature and illuminance in similar ways. According to the DOE SEL method, using higher CCT lamps with lower lumen output (which is directly related to wattage) will maintain equivalent brightness and visual acuity. DOE claims that this different way of thinking about illumination can provide energy savings of 20 to 40% [DOE 2012b, PNNL 2006]. However, even if true, for visual acuity and brightness perception, these are not the only determinants of occupant satisfaction with a lighting system.

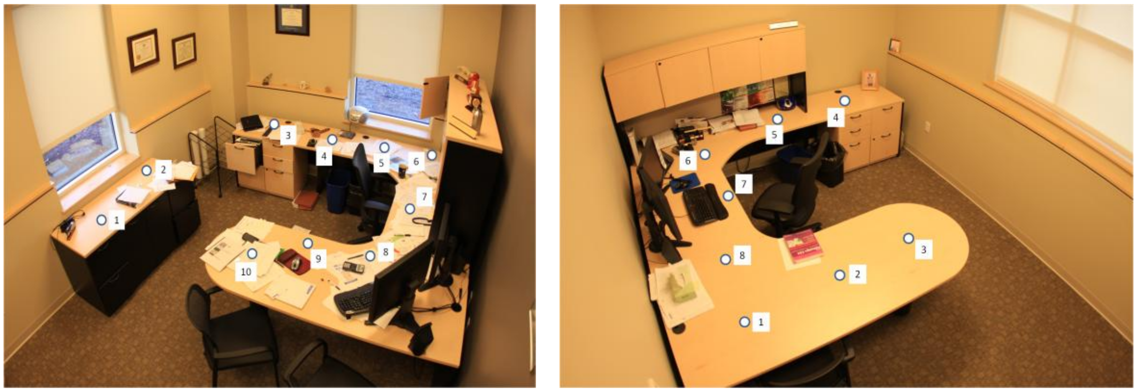
This paper describes a field study designed to examine the practicality of the DOE SEL method for lumen output reduction, and thus energy use reduction, in a typical office building, focusing on brightness perception, visual comfort, and satisfaction of color temperature.

# 2. METHOD

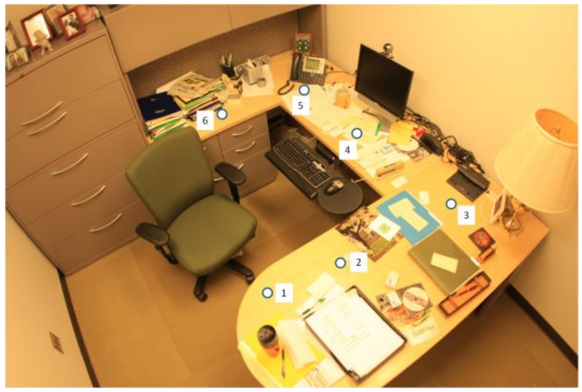
## 2.1. Setting

The study was carried out in a four-story office building in Central Pennsylvania. The areas included covered open-plan areas, cubicles, private offices, common areas, and conference rooms, where the occupants spent most of their time during working hours.

The general lighting in these areas was provided by 2 ft × 4 ft recessed troffers or indirect pendant luminaires. The existing conditions for each luminaire featured two 32 W, T8 linear fluorescent lamps with a CCT of 3500 K, a Color Rendering Index (CRI) of 85, and mean lumen output of 2945 lm. Supplementary under-cabinet task lights and table lamps were also provided to some occupants. There were occupancy sensors, shades, and blinds in some areas, which could be adjusted by occupants. All the fluorescent luminaires, including troffers, pendant luminaires, and under-cabinet lights, were included in this study. Figure 1 (a) – (c) are the photographs of three private offices in this study.



(a) (b)




(c)

**Figure 1 Photograph of three private offices (Office A, Office B, and Office C). The mean illuminances are calculated from the measurements taken around the locations labeled in the figures.**

## 2.2. Participants

All potential participants were recruited either via e-mail, telephone, or in person. There were no criteria to exclude participants. Twenty-eight participants initially agreed to participate in the study. During the process of the experiments, two dropped out. Totally, twenty-six participants finished the entire study, though not all of them completed all of the surveys.

Of these 26 participants, 11 were males. Age ranged from 23 to 55 years with a mean of 38.8 years and a standard deviation of 10.01 (one female participant did not disclosure her age). Two of them were Black or African American; the others were White. None of them reported abnormal color vision and none had knowledge about the lamps that were employed in the study. All the participants had worked in the work area for more than four months. Ten participants had daylight in their personal work areas and the other 16 did not.

## 2.3. Procedure

The study lasted about three months from October 2011 to January 2012, which included the Thanksgiving and Christmas holidays, during which times the building was closed. Four luminous conditions were included in this study, which were purposely selected to test the DOE SEL method, as later discussed in detail.

The participants experienced a baseline condition followed by the four treatment conditions and then returned to the baseline condition; each treatment lasted two weeks. In the first week of each treatment period, the participants adapted to the luminous environment; in the second week, they completed brief assessment surveys three times daily (that is, in the morning before work, at lunch time, and at the end of work) using a smart phone, which was kept by each participant during the study. A more comprehensive survey was completed by the participants prior to the start of the treatment conditions and on the last day of each treatment period and the last baseline condition through the internet using a personal computer. All the fluorescent lamps throughout the area were replaced on the Saturday after each treatment period without notification to the occupants. The entire work environment had uniform light source color allowing the occupants to be completely adapted to the treatment (or baseline) condition.

## 2.4. Variables

### 2.4.1. Independent variables

The four treatment conditions were created and organized as a two by two factorial design, comprising two levels of CCT (that is, 3500 and 5000 K) and lumen output (that is, 2330 and ≈ 3000 lm) as shown in Table 1. Thus, the independent variables were CCT and lumen output of the linear fluorescent lamp. These four lamp types are commercially available and were purchased through normal channels.

**Table 1 Index of the four light settings (A, B, C, D) with corresponding CCT and lumen output. The order of treatment experienced by the participants was from A to D. A and C had a CRI of 85; B and D had a CRI of 82. The lumen output of B and C was 2935 and 3000 lm, respectively.**

| | | Lumen Output (lm) | |
|---|---|---|---|
| | | 2330 | ≈ 3000 |
| CCT (K) | 3500 | A | C |
| | 5000 | D | B |

In addition to CCT and lumen output, the availability to daylight in participant's office was also regarded as an independent variable, which was hypothesized to affect the dependent variables.

### 2.4.2. Dependent variables

The brief assessment surveys and comprehensive surveys covered different aspects: background information, information about working area, lighting belief, satisfaction with indoor environment conditions (lighting, air quality, noise, privacy, and thermal comfort), health and wellbeing, mood, control behavior, and productivity. Copies of the surveys are available upon request.

This paper mainly focuses on three semantic differential-scaled questions that were included in two daily surveys—at lunch time and at the end of work—regarding perception of luminous environment. The three questions and responses were:

- Q1: Considering your time at work this morning (or afternoon), how bright was the lighting in your work area? (Response: "too dim" to "too bright");
- Q2: Considering your time at work this morning (or afternoon), how satisfied were you with the visual comfort of the electric lighting in your work area? (Response: "very unsatisfactory" to "very satisfactory");
- Q3: Considering your time at work this morning (or afternoon), the color temperature of the electric lighting in your work area was? (Response: "too cool" to "too warm").

A slider was provided on the smart phone for each question. The responses were coded on scales from 1 to 100.

### 2.5. Illuminance measurements

Illuminance measurements were taken on desktop surfaces in three private offices under each treatment. The measurements were taken at approximately the same locations, as indicated in Figure 1 (a) – (c). In Office A and B, two illuminance conditions were measured: that provided by daylight only and that provided by the overhead luminaires and daylight. The illuminance provided by just the overhead luminaires was calculated as the difference between these two measurements. In Office C, the illuminance provided by overhead luminaires only was measured directly since there was no daylight. Table 2 summarizes the means and standard deviations in the three offices under the four treatment conditions. It can be observed that the relationships between the mean illuminances provided by the overhead luminaires only were similar to the ratios of lumen output of the four lamp types.

**Table 2 Mean illuminances and standard deviations in three private offices (1. these illuminance levels were measured directly using an illuminance meter in the experiment space; 2. these illuminance levels were calculated from the measurements; 3. one overhead luminaire was not working when the measurements were taken)**

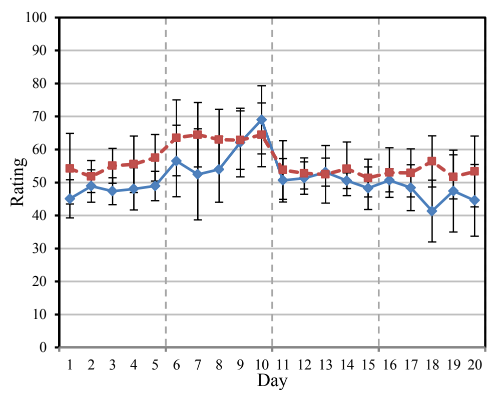
| | Lamp type A | | Lamp type B | | Lamp type C | | Lamp type D | |
|---|---|---|---|---|---|---|---|---|
| | Mean | Std. dev. | Mean | Std. dev. | Mean | Std. dev. | Mean | Std. dev. |
| Office A[2] | 203.2 | 58.04 | 354.5 | 115.50 | 384.5 | 85.23 | 246.0 | 85.36 |
| Office B[2] | 188.9 | 51.97 | 317.9 | 93.60 | 288.4 | 74.48 | 191.5 | 56.25 |
| Office C[1] | 545.8 | 127.54 | 709.8 | 177.83 | 443.3[3] | 110.64 | 576.2 | 145.58 |

## 3. RESULTS

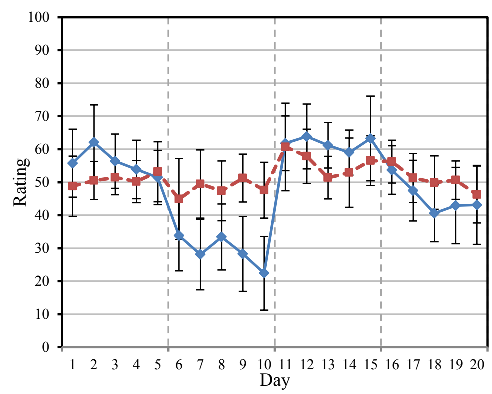
Table 3 summarizes the mean ratings with standard deviations given by the participants, and the number of responses in each treatment period. Figure 2 (a) – (c) show the mean ratings with standard deviations given by the participants on each day during the four treatment periods. Some responses provided by the participants were regarded as unreliable data (for example, the participant did not use the overhead luminaires during that week, the participant was not in the office in the morning/afternoon, or the participant completed the lunch-time survey and the end-of-work survey at the same time), which were excluded from the analyses.

**Table 3 Mean ratings and standard deviations given by the participants**

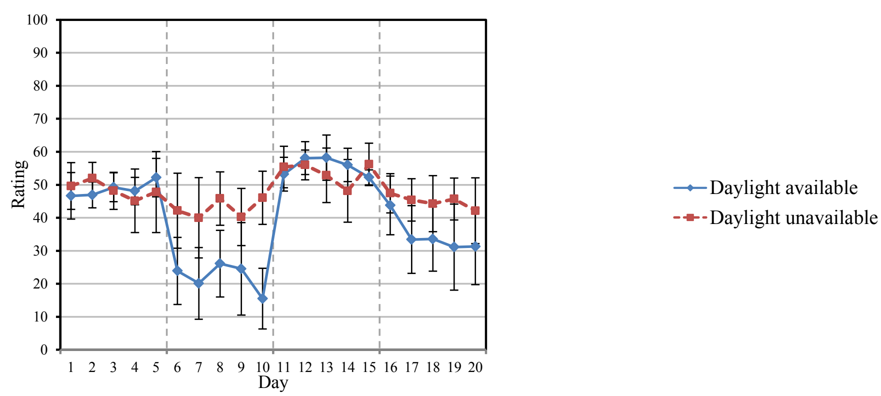
| Daylight availablity | Lamp Type | Number of responses | Q1: Brightness | | Q2: Visual comfort | | Q3:Color temperature | |
|---|---|---|---|---|---|---|---|---|
| | | | Mean | Std. dev. | Mean | Std. dev. | Mean | Std. dev. |
| Yes | A | 84 | 47.61 | 9.91 | 55.73 | 17.80 | 48.65 | 10.00 |
| | B | 89 | 58.51 | 22.41 | 29.55 | 21.31 | 22.26 | 21.63 |
| | C | 67 | 50.96 | 8.71 | 61.91 | 14.74 | 55.72 | 9.09 |
| | D | 84 | 46.35 | 17.13 | 45.54 | 18.80 | 34.74 | 20.47 |
| No | A | 70 | 54.60 | 13.15 | 50.67 | 12.13 | 48.71 | 12.76 |
| | B | 75 | 63.60 | 17.00 | 48.24 | 16.70 | 42.88 | 17.18 |
| | C | 68 | 52.82 | 11.83 | 55.65 | 14.91 | 53.76 | 12.16 |
| | D | 88 | 53.43 | 15.29 | 50.91 | 14.37 | 45.06 | 14.42 |




(a)




(b)




(c)

**Figure 2 The mean ratings with standard deviations given by participants for the brief assessment surveys on each day during the four treatment periods; the lunch-time survey and end-of-work survey were combined. (a) brightness perception; (b) visual comfort; (c) satisfaction of color temperature.**

Three linear mixed-models were fit to the responses given by the participants on three questions, with one each for brightness perception, visual comfort, and perception of color temperature. Table 4 summarizes the results of these mixed-models.

**Table 4 Statistical significance (p-values) for main effects and interaction items in linear mixed-model for brightness perception, visual comfort, and perception of color temperature.**

| | | Q1<br>Brightness | Q2<br>Visual comfort | Q3<br>Color temperature |
|---|---|---|---|---|
| Main effect | CCT | 0.001 | < 0.001 | < 0.001 |
| | Lumen output | 0.037 | 0.199 | 0.301 |
| | Daylight availablity | 0.211 | 0.737 | 0.360 |
| 2-way interaction | CCT × Lumen output | < 0.001 | < 0.001 | < 0.001 |
| | CCT × Daylight availablity | 0.968 | < 0.001 | < 0.001 |
| | Lumen output × Daylight availability | 0.490 | 0.253 | 0.097 |
| 3-way interaction | CCT × Lumen output × Daylight availability | 0.400 | 0.011 | 0.066 |

## 3.1.Brightness perception

The result of the mixed-model revealed that CCT, lumen output, and the two-way interaction between them were significant factors affecting the brightness perception.

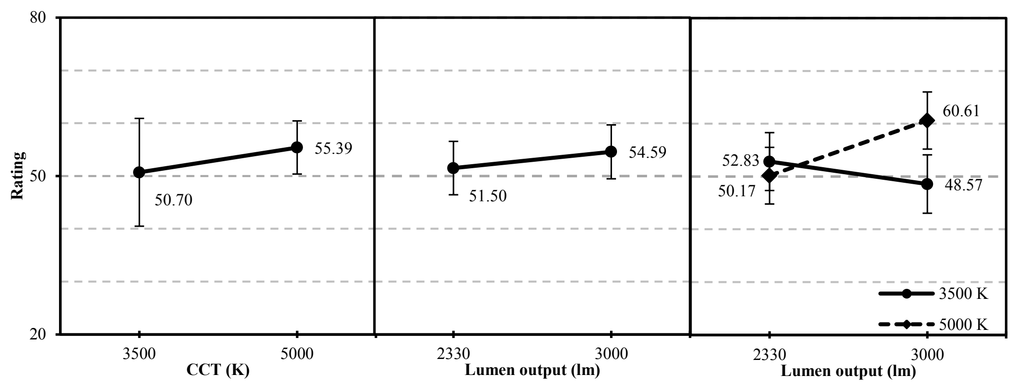



**Figure 3 Main effects and two-way interaction plots that were significant factors in the mixed-model for brightness perception.**

As shown in Figure 3, the luminous conditions at 5000 K were rated to be brighter than those at 3500 K. And the luminous conditions using lamps with 3000 lumens were rated to be brighter than those with 2330 lumens.

In addition to considering CCT and lumen output independently, the existence of a statistical interaction between CCT and lumen output is more important. The participants thought the luminous environment provided by lamp type B (5000 K with 3000 lm) was too bright. In contrast, mean ratings were from 45 to 55 for the other three lamp types. Since a rating of 50 means neither too bright nor too dim, these ratings suggest that the participants thought the brightness was just right under those three luminous conditions.

## 3.2.Visual comfort

For visual comfort, CCT, the two-way interactions between daylight availability and CCT, and CCT and lumen output, and the three way interaction between daylight availability, CCT, and lumen output, were significant factors.

Generally speaking, the lamps with 5000 K were rated to be less comfortable than those with 3500 K, especially when the 5000 K was combined with 3000 lm, as shown in Figure 4. Specifically, for the participants who did not have daylight in their working space, the four luminous conditions had similar visual comfort. For those who had daylight, the luminous conditions provided by 5000 K were rated to have lower visual comfort than those provided by 3500 K, especially when combined with high lumen output.

### 3.3.Satisfaction of color temperature

For satisfaction of color temperature, CCT and the two-way interaction between daylight availability and CCT, CCT and lumen output were significant factors, as shown in Table 4.

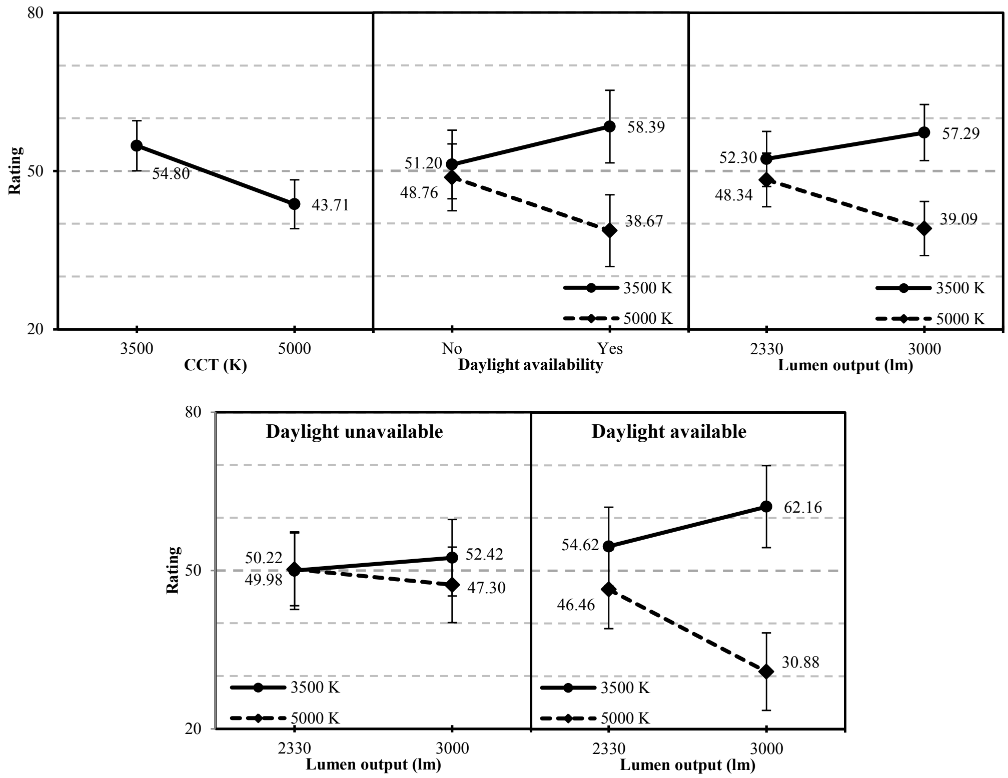



**Figure 4 Main effect of CCT, two-way interaction, and three-way interaction plots that were significant factors in the mixed-model for visual comfort.**

As shown in Figure 5, the 5000 K conditions were thought to be too cool, especially when the higher lumen output was in place; while the 3500 K conditions were approximately neutral regardless of lumen output. For the participants with daylight in their office, 5000 K was especially judged to be too cool.

The ratings of brightness perception, visual comfort, and satisfaction of color temperature were correlated with each other. The conditions at 5000 K were regarded to be too bright, too cool, and thus less comfortable than those at 3500 K. The condition with higher CCT combined with higher lumen output was regarded as too cool and least comfortable, especially for those with daylight in their offices.

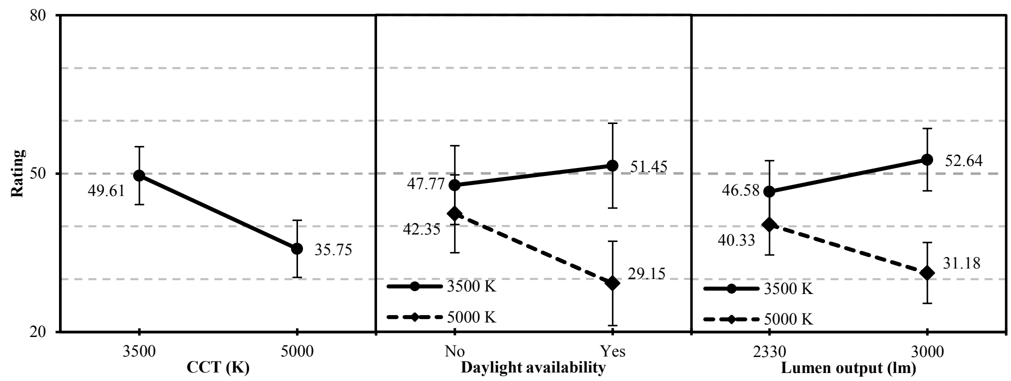



**Figure 5 Main effect of CCT and two-way interaction plots that were significant factors in the mixed-model for satisfaction of color temperature.**

# 4. DISCUSSION

The existence of the interaction between CCT and lumen output reveals that when the lumen output was relatively low, the occupants did not have a strong opinion about CCT. However, when the lumen output was high, CCT influenced the occupants' perception of the interior environment, especially for those had daylight availability.

Among these four luminous conditions employed in this study, the difference between lamp type C (3500 K with 3000 lm) and lamp type D (5000 K with 2330 lm) should be investigated further because it matches DOE's SEL concept. Though the brightness perception between these two lamp types was not statistically different, lamp type C was rated to be more comfortable than lamp type D, which was rated to be too cool. Thus, the energy consumption can be reduced about 30% by replacing lamp type C with lamp type D, however, the participants in this study felt that the lighting was too cool and gave that condition lower ratings of visual comfort. Our findings on visual comfort contradict the field studies conducted by PNNL, in which no significant difference was observed between lamp pairs that were similar to this study [PNNL 2006]. Though the effectiveness of using higher CCT with lower lumen output to provide the same brightness was supported by this study, it does not necessarily mean that the lamps with higher CCT will always appear brighter [Hu and others 2006, Houser and others 2009].

The effect of daylight availability in this study merits comment. The color temperature of daylight ranges from 5300 K for overcast sky to above 6000 K for clear sky [Begemann and others 1997]. Though the conditions at 5000 K were closer to the color temperature from daylight than the conditions at 3500 K, the participants with daylight availability felt uncomfortable working under the lamps at 5000 K and they thought the conditions at 5000 K were too cool, especially when higher lumen output was in place. Such a finding is inconsistent with the recommendation in the *Advanced Energy Design Guide for Small to Medium Office Buildings* [ASHRAE 2011]. The researchers from PNNL did not find an effect of daylight availability in their field studies [PNNL 2006]. On the other hand, Begemann and his colleagues found the preference of the color temperature of electric lighting did not correlate with the color temperature of daylight [Begemann and others 1997]. Because of the limited number of participants, the effect of orientation of the office with daylight cannot be investigated.

## 5. CONCLUSION

Four luminous conditions were employed and organized as a two by two factorial design in this field study, comprising two levels of CCT (that is, 3500 and 5000 K) and lumen output (that is, 2330 and ≈ 3000 lm). For brightness perception, the participants rated the luminous conditions with higher CCT or higher lumen output as brighter than those with lower CCT or lower lumen output. The condition with both higher CCT and higher lumen output was thought too bright. CCT was a significant factor for the perception of visual comfort and the satisfaction of color temperature, while lumen output was not. The luminous conditions at 5000 K were regarded as less comfortable than those at 3500 K. 5000 K was judged to be too cool, when the higher lumen output was in place. For the participants with daylight in the office, 5000 K was especially judged to be too cool.

Though the condition with higher CCT and lower lumen output was able to provide comparable brightness perception as that with lower CCT and higher lumen output—as claimed by DOE's SEL method for reducing energy consumption—the reduction in energy consumption was achieved at the expense of visual comfort, especially in the environment with daylight availability.

## 6. ACKNOWLEDGEMENTS

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# ANALYSIS OF BALANCE BETWEEN MODELING ACCURACY AND COMPUTATIONAL SPEED FOR A HYBRID RAY-TRACING AND RADIOSITY METHOD USED IN LIGHTING SIMULATION

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## ABSTRACT

A new hybrid ray-tracing and radiosity method was developed to adopt a balance between computational speed and accuracy when simulating building interior illuminance distributions. The method is able to model spaces with highly specular components, highly diffuse components (i.e., walls, floors, roller shades), as well as components with mixed properties that strongly affect the daylighting performance of the space (i.e., venetian blinds and light-shelves). The specular components are processed with a forward ray-tracing method, while the diffuse components are processed with a radiosity method. The concept of shining factors is used to separate luminous flux though components with mixed properties, while parameter settings affect both simulation speed and accuracy of results.
In this paper, the amount of light rays (tracing resolution) used in the ray-tracing part and the grid size (space resolution) used in the radiosity part are investigated to analyze the impact of those parameters when predicting work plane illuminance and lighting energy consumption. Use of high numbers of generated rays and high grid density can provide detailed illuminance results. However, the penalties associated with computational time may exceed the accuracy requirements. Recommendations for best settings for different modeling cases are provided so as to balance accuracy versus computational speed. The outcomes of this study can provide useful information for modeling daylighting performance of spaces with specular, diffuse and mixed reflection components such as blinds and light-shelves.

**Keywords:** Daylighting, Shading, Radiosity, Ray Tracing, Simulation

## 1. INTRODUCTION

Shading devices are widely used in both commercial and residential buildings to maintain occupancy's visual and thermal comfort, as well as to reduce energy usage for heating, cooling, and lighting. Except the function of blocking direct sunlight, some shading devices such as light shelves and venetian blinds have the ability to redirect penetrating sunlight deeply into desirable locations in the building by using highly specular materials. Different shading devices can be installed in different sections of the façade to realize multi-functional purposes. The performance of shading devices is impacted by the control strategies of both shading devices and lighting system. To select an energy-efficient façade configuration and to implement an energy-saving control loop, a good predictive model is needed to decide the best designs and operations. A daylighting-and-thermal model (Tzempelikos and Athienitis 2005; Kim and Park 2012) which have the abilities to calculate indoor environmental variables (ex: illuminance distribution and visual or thermal comfort) and overall energy usage is required in cases related to complex fenestration systems.

A new hybrid model for calculating illuminance distribution and solar heating gain is employed in the predictive model (Chan and Tzempelikos 2012) to investigate the balance between computational speed and accuracy of simulation. Traditionally, there are two ways to predict indoor daylighting distributions and solar heat gains in spaces with fenestration systems: ray tracing- and radiosity-based methods. Radiance software (Ward and Shakespeare 1998) which uses backward three-dimensional ray tracing algorithms is one of the most popular tool to generate accurate and detailed illuminance distributions and has been applied in several case studies for static simulation. Recent modifications allowed dynamic simulation including complex fenestration systems with bidirectional distributions functions (Ward et al. 2011). Daysim, a Radiance-based tool (Reinhart and Walkenhorst 2001), extended daylighting modeling capabilities to annual simulation including shading devices (Reinhart and Breton, 2009). The concept of backward ray tracing presents what the observer sees by emitting rays from the eye or the reference point back to the light source which saves the time to compute light rays not ending up at the eye. But when applying this to all the surfaces inside the room, several reference points need to choose and the computational time increases. Forward ray-tracing algorithms were also used to provide more intuitive and full-scale results of illuminance distributions in the entire room (Campbell and Whittle 1997). However, the disadvantages of pure ray tracing methods (both forward and backward) are time and computational memory requirements, especially for surfaces made by highly diffuse materials such as common interior wall surfaces (large amount of rays should be sampled to accurately model anisotropic effects in the ray tracing process).

To speed up the calculation process, radiosity-based methods were then widely-used (Athienitis and Tzempelikos 2002; Lehar and Glicksman 2007) and applied in most of annul-based simulating applications. All sub-surfaces are assumed to be perfect diffusers and high speed computation is achieved when the amount of sub-surfaces is small. On the other hand, when highly specular properties are involved, the accuracy becomes questionable (Tsangrassoulis and Bourdakis 2003).

A hybrid ray-tracing and radiosity model was then developed to overcome the issue of maintaining the balance between accuracy and computational time. In the hybrid model, the ray-tracing method is used to process the specular characteristics (e.g. venetian blinds and reflective light shelves) and the radiosity method is used to process the diffuse characteristics. However, some issues within this method still have to be discussed. In the ray tracing module, the sample size (ray numbers) is a topic of discussion. When the sample size is too small, it may produce inconclusive results. For the radiosity part, although faster, the burdens of calculating view factors increase and memory requirements increase when space resolutions (sub-surface numbers) are high. High numbers of generated rays and high grid density can provide detailed illuminance results; however, the penalties associated with computational time may exceed the accuracy requirements. In this paper, the amount of light rays (tracing resolution) used in the ray-tracing part and the grid size (space resolution) used in the radiosity part are investigated to analyze the impact of those parameters when predicting fenestration (glazing/shading) system transmittance interior and work plane illuminance.

Annual simulation requires accurate and convenient descriptions of fenestration system solar-optical properties for estimation of lighting and thermal performance as well as for real time model-based control applications. In this study, a complex case with interior movable venetian blinds is presented.

## 2. HYBRID RAY-TRACING AND RADIOSITY METHOD

In the hybrid method, for surfaces that have both diffuse and specular characteristics, the incoming luminous flux was split to an isotropic part (specular), which is solved by the ray tracing method, and to an anisotropic part (diffuse), which is solved by the radiosity method. Also, the concept of "shining factors" (Pfrommer and Lomas 1996) is used to quantify these two characteristics. The shining factor is defined as the ratio between the diffuse-reflected portion and the total-reflected portion (1 represents a perfect diffuser and 0 represents an ideal specular reflector).

Here we focus on daylighting but the basic modeling method is the same for solar radiation transport and estimation of solar gains. In the building simulation process, daylighting transmitted through glass consists of two parts – diffuse illuminance and direct illuminance. If there is a glazing component with mixed characteristic, the diffuse part is dealt with radiosity method (for blinds, two-dimensional radiosity calculations proposed by EnergyPlus (2007) is used; for light shelves, the sunlight striking area is considered as one of diffuse surfaces in three dimensional radiosity calculations) and the direct part is dealt with ray-tracing calculations. This calculation module computes the amount of diffuse illuminance transmitted to inside and the amount reflected back to the glass (if any), as well as the diffuse-to-diffuse transmittance and reflectance of the shading devices.

In the ray tracing method for direct illuminance calculation, the rays are uniformly sampled from the outside boundary (ex: glass for no exterior shading device case) with same directional vector based on the position of sun. Then based on the position and directional vector, the collision locations for each of the rays are calculated. There are three possible ray collision locations: (i) striking a diffuse surface (ii) striking a highly specular surface and (iii) striking an outside boundary. If the ray strikes on a diffuse surface, it immediately stops and the accumulated amount is later used in three-dimensional radiosity method. If the ray strikes on a highly specular surface, the impact of the shining factor will be considered; the ray's representing illuminance attribution will be split between the direct-specular component and the direct-diffuse component. The amount of direct-diffuse is sent to the radiosity module for further processing. The direct-specular part needs to be tracked continuously until the entire specular component becomes diffuse or is absorbed. If the ray strikes an outside boundary such as the window, it is assumed to become diffuse to simplify the calculation process. In case of exterior shading devices present, the part striking the outside boundary will just exit the cavity. But for interior shading devices, we need to consider the inter-reflection effects between the glass and the shading system inside the cavity when dealing with direct-diffuse component (combined with diffuse-diffuse calculations).

The total diffuse and direct transmitted light is considered as the initial luminous exitance of the system in the room-level three dimensional radiosity calculations, to obtain the final illuminance distributions and work plane illuminances. In the 3-D radiosity calculations, each of the interior surfaces is first divided into small rectangular sub-surfaces with equal areas. The uniformity of sub-surfaces can save time for calculating view factors. The relative size of the sub-surfaces is one of the major issues discussed in this paper. The detailed methodology was published in previous research (Chan, 2012). This paper is focused on the efficiency and accuracy discussion.

# 3. RESULTS

### 3.1 Simulation Case Description

The baseline model is a 4m (length) by 4m (width) by 3m (height) zone with one south facing window. The window size is 2m (length) by 1m (height). The glazing system is composed of double-glazed clear glass (transmittance is 0.781 for visible light and 0.606 for solar radiation at normal incidence). The work plane height is set as 0.8m. Interior venetian blinds are used as a shading system. The width and gap length of slats are both equal to 0.1 m. The slats are flat with no thickness, with a reflectance equal to 0.7. The shining factor is set to 0 in order to simulate the most sensitive case which is happened in perfect specular properties. The reflectance of interior floor, ceiling and walls are equal to 45%, 80% and 50% respectively. In the simulation process, it is assumed as no other obstacles in the room.

### 3.2 Generated Ray Density Analysis

To analyze the impact of the ray numbers on blind direct-specular transmittance, we generated 100 samples (100 times simulation) of five different ray number sets (1000/m$^2$, 2000/m$^2$, 4000/m$^2$, 8000/m$^2$, 16000/m$^2$) which correspond to the total generated number of rays divided by the window area. Different slat angle and profile angle combinations were investigates as shown in Figure1. As expected, high ray density decreases standard deviation. Most of the differences between maximum and minimum values are small: the largest one is only 0.029 which happened for 45 degrees slat angle 20 degrees profile and low density ray generation. There are several combinations having no calculation error, corresponding to the cases when all rays have the same number of bounces. For example, when the slat angle is -20 degrees and the profile angle is 20 degrees, the transmittance would be 100% if we ignore the thickness of slat –based on the analytical model. If we use a ray tracing model, all the rays have zeros bounces no matter how many rays are generated. A higher number of bounces will cause higher bias. Table 1 shows the computational speed and standard deviation of 4 cases with slat angle equal to -20 degrees. From Case 1, we can see that the standard deviation remains the same from 1000/m$^2$ to 16000/m$^2$ ray density, but the computational time increases to 11.2 times the original. From Case 2 to Case 4, the standard deviation decreases when the ray numbers increase, but the penalty of computational time is much higher than the increase in accuracy. For example, in Case 2, increasing ray density from 1000/m$^2$ to 2000/m$^2$ will increase computational time by 1.47 times, but the standard deviation decreases by 74%. Based on this analysis, a ray density of 2000/m$^2$ is considered adequate to maintain desired accuracy in venetian blind transmittance calculations.

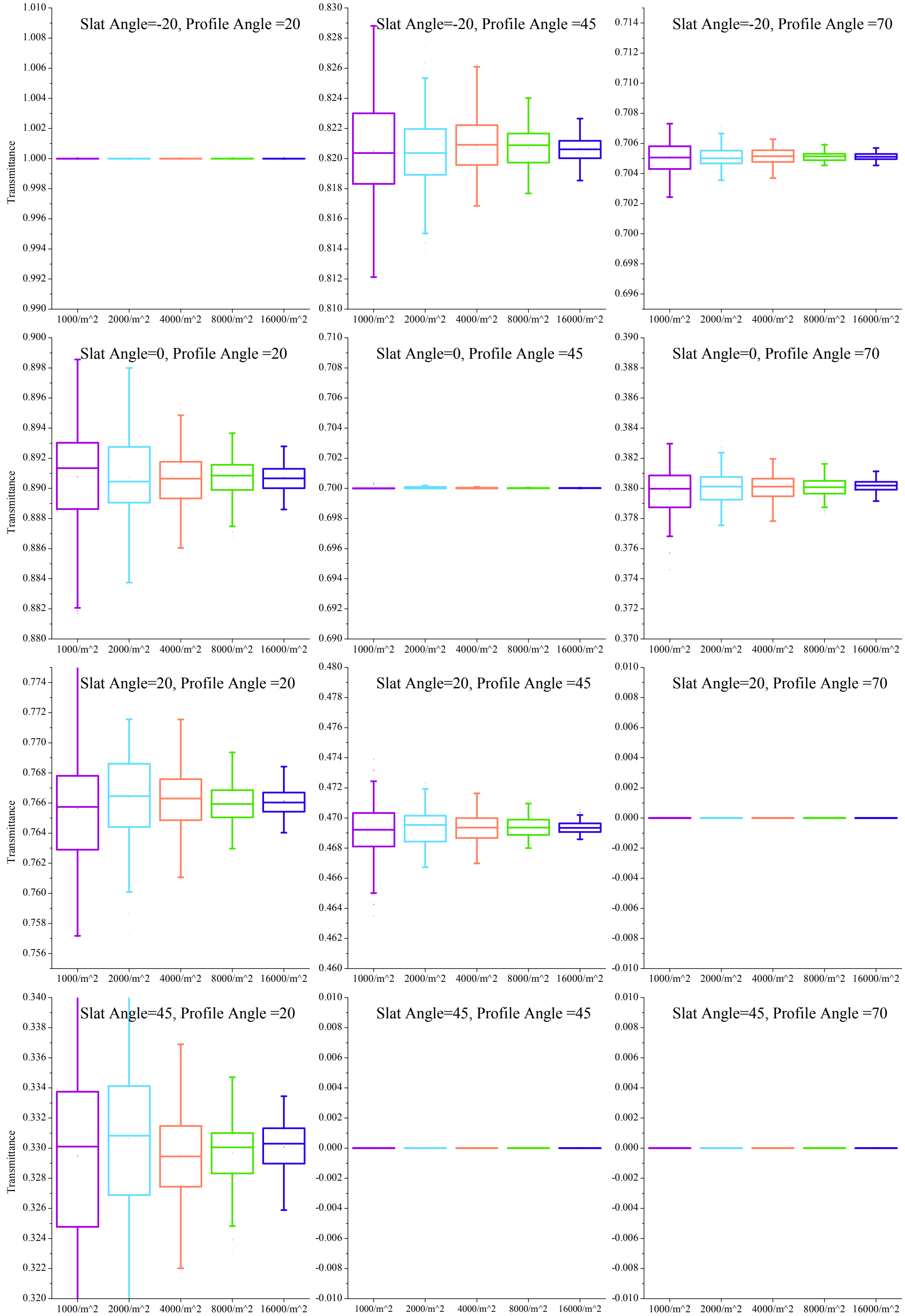
**Table 1: Comparison of mean values, standard deviation and computational time as a function of generated rays density for four blind rotation cases**

| | Case1: Slat Angle = -20, Profile Angle = 20 | | | | | Case2: Slat Angle =0, Profile Angle = 20 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Data** | 1000/m² | 2000/m² | 4000/m² | 8000/m² | 16000/m² | 1000/m² | 2000/m² | 4000/m² | 8000/m² | 16000/m² |
| **Mean** | 1 | 1 | 1 | 1 | 1 | 0.891 | 0.891 | 0.891 | 0.891 | 0.891 |
| **STD** | 0 | 0 | 0 | 0 | 0 | 0.004 | 0.003 | 0.002 | 0.001 | 0.001 |
| **CT** | 0.083s | 0.146s | 0.249s | 0.512s | 0.926s | 0.141s | 0.208s | 0.385s | 0.758s | 1.499s |
| **STD*** | N | N | N | N | N | N | N/1.34 | N/1.92 | N/2.83 | N/3.95 |
| **CT*** | N | 1.76N | 3.02N | 6.20N | 11.20N | N | 1.47N | 2.73N | 5.36N | 10.61N |
| | **Case3: Slat Angle = 20, Profile Angle = 20** | | | | | **Case4: Slat Angle = 45, Profile Angle = 20** | | | | |
| **Data** | 1000/m² | 2000/m² | 4000/m² | 8000/m² | 16000/m² | 1000/m² | 2000/m² | 4000/m² | 8000/m² | 16000/m² |
| **Mean** | 0.766 | 0.766 | 0.766 | 0.766 | 0.766 | 0.329 | 0.331 | 0.329 | 0.33 | 0.33 |
| **STD** | 0.00404 | 0.0028 | 0.0022 | 0.00135 | 9.51E-04 | 0.00625 | 0.005 | 0.00351 | 0.00223 | 0.00163 |
| **CT** | 0.166s | 0.298s | 0.576s | 1.117s | 2.228s | 0.235s | 0.450s | 0.875s | 1.725s | 3.435s |
| **STD*** | N | N/1.44 | N/1.84 | N/2.99 | N/4.25 | N | N/1.25 | N/1.78 | N/2.80 | N/3.83 |
| **CT*** | N | 1.79N | 3.47N | 6.73N | 13.41N | N | 1.92N | 3.72N | 7.34N | 14.625N |

*STD= Standard Deviation, CT=computational time relative to low density (1000 rays/m²)

### 3.3 Grid Size Analysis

In the second part of this study, the impact of grid size on interior illuminance distribution was investigated. For the radiosity method, the most time-consuming part is the view factors calculation. Theoretical view factor calculations require double integrating across the area of patches; therefore it is complex and time-consuming to solve these equations directly. In rectangular rooms, we can cut the meshes to small rectangular sub-surfaces, and then use analytical solutions to solve the problem. However, the original grid size selection is still a key point of the balance between accuracy and computational time. Figure 2 presents work plane illuminance results for 45° profile angle and 0° slat angle (horizontal blinds). All of the direct daylight is reflected to the ceiling, and there is no direct-specular light falling on the work plane (the computational time information is also provided in the figures). The 40 by 40 grid size (high resolution case) provides almost the same results with the 20 by 20 grid size case, but the computational time is 13 times higher. The 8 by 8 gird size case has slight differences but the computational decreases more than 200 times. Finally, the 4 by 4 grid size (low resolution case), although super fast, fails to capture higher illuminance spots.


Slat Angle=-20, Profile Angle =20
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Slat Angle=-20, Profile Angle =70
Slat Angle=0, Profile Angle =20
Slat Angle=0, Profile Angle =45
Slat Angle=0, Profile Angle =70
Slat Angle=20, Profile Angle =20
Slat Angle=20, Profile Angle =45
Slat Angle=20, Profile Angle =70
Slat Angle=45, Profile Angle =20
Slat Angle=45, Profile Angle =45
Slat Angle=45, Profile Angle =70
Transmittance
1000/m^2
2000/m^2
4000/m^2
8000/m^2
16000/m^2

**Figure 1: Analysis of the impact of generated rays' density on venetian blind transmittance for different slat and profile angles.**

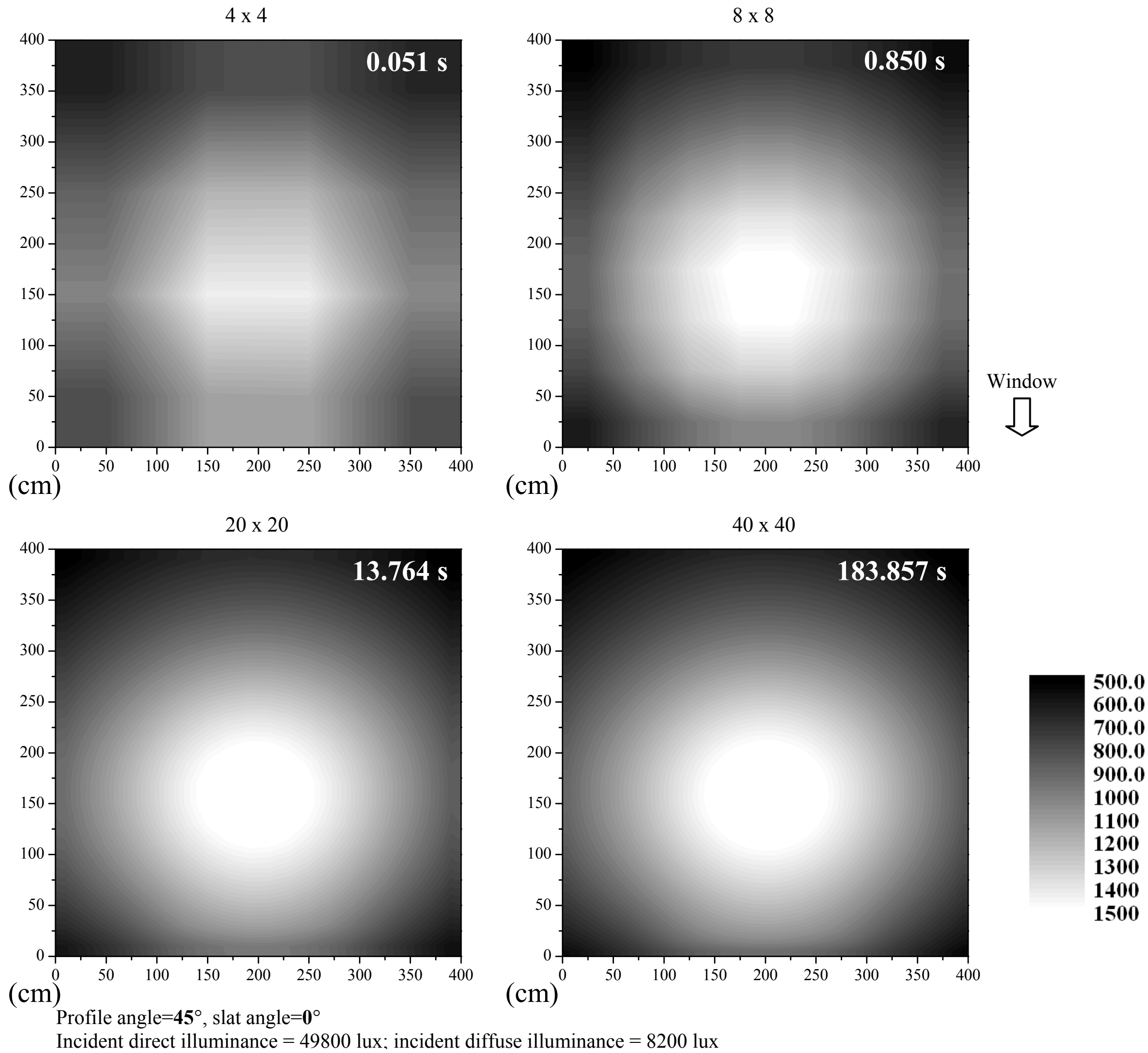


**Figure 2: Work plane illuminance results with different grid resolutions (no direct-specular light incident) and computational times**

Figure 3 presents work plane illuminance results for the case of 45° profile angle and -10° slat angle (blinds rotated inwards). For this configuration, Part of direct light strikes the work plane and results in high illuminance values near the window (located on the x-axis). Other bright illuminance regions appear because of reflected light from other surfaces. Even the highest resolution (40 by 40) could not accurately capture the projected blind patterns. Again, the 40 by 40 and 20 x 20 resolutions have similar results, while the 8 by 8 case cannot clearly present values very close to the window (less than 25 cm).

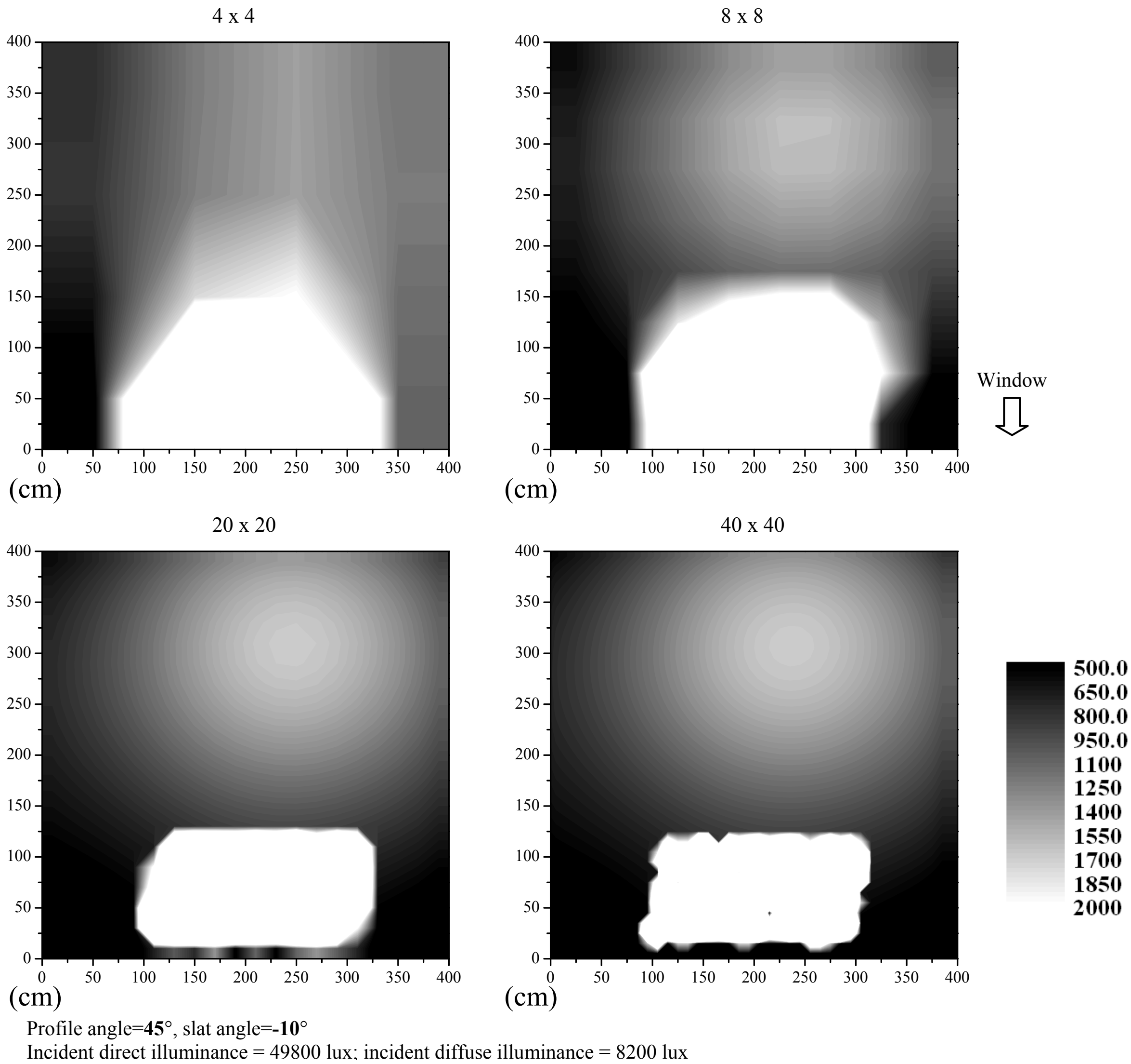


**Figure 3: Work plane illuminance results with different grid resolutions (with direct-specular light incident) and computational times**

In order to systematically compare the results of the different grid resolutions, data from all cases were interpolated to a 40 x 40 equivalent grid size and were compared to the original 40 x 40 resolution using the mean square root error as an index (Table 2). The interpolated illuminance values along the middle of the room (perpendicular to the window) are also compared in Figure 4. For the case without direct-specular light, the 4 by 4 case has a RMSE higher than 100lux, which will cause errors in daylighting simulation and blind control-based models. From Figure 4, the peak error in the middle line is around 200lux (similarly for other grid resolutions). The 8 by 8 case slightly underestimates the illuminance but the RMSE is only 42lux. One of the main reason to cause error in the simulation without direct-specular light is the wrong prediction close to the boundary (walls or windows), but the illuminance values near the boundary area do not critically affect the daylighting simulation results. However, for the case with direct-specular light on the work plane, the 40 by 40 case captures the peak value and the dark and bright patterns caused by the blinds much better than all the other three (peaks and lows in Fig. 4). Due to the impact of the projected sun patches (transmitted between slats from direct-specular light), the RMSE values of the other three cases are quite high. A careful look at Figure 4 shows that except for the projected blind areas, the rest of the results are generally in good agreement. Note that for most practical applications direct-specular light would be avoided therefore, considering the balance of computational speed and accuracy, the 8 by 8 grid for a 4m by 4m room is considered adequate.

**Table 2: RMSE of the illuminance distribution with interpolated data using the 40 x 40 resolution as a comparative basis**

| | profile angle=**45**°, slat angle=**0**° (without direct-specular light) | profile angle=**45**°, slat angle=**-10**° (with direct-specular light) |
|---|---|---|
| 4x4 | 112.44 (lux) | 1156.93 (lux) |
| 8x8 | 42.11 (lux) | 1013.32 (lux) |
| 20x20 | 21.54 (lux) | 788.54 (lux) |

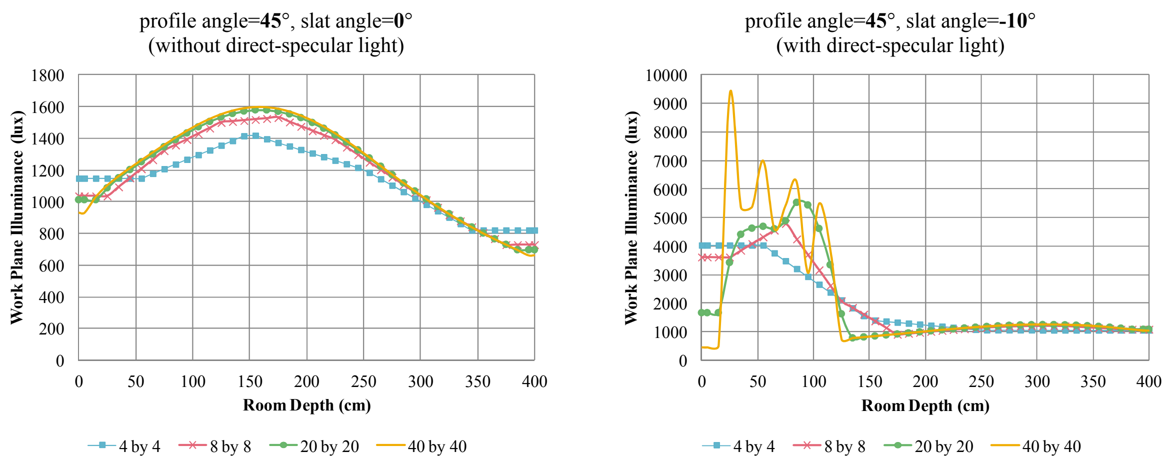


**Figure 4: Work plane illuminance across the middle of the room (perpendicular to the window) using the interpolated data from different grid resolutions with and without direct light incident**

## 4. CONCLUSION

This paper analyzed the impact of generated ray numbers density and grid resolution in a newly developed hybrid ray-tracing and radiosity method for spaces equipped with interior venetian blinds or any other daylighting/shading system that may include specular components. Blind transmittance results and work plane illuminance distributions and statistical parameters were presented for different densities, grid resolutions, blind tilt angles and profile angles, including direct-specular light incident on the work plane.

The comparative sensitivity analysis showed that 2000 rays per square meter are enough for estimating the transmittance through a venetian blind system with 10cm width slats. For a typical private office space (4m x 4m), a grid resolution of 8 x 8 (grid size equal to 0.5m) is considered adequate for prediction of interior illuminance distributions that can be used for lighting simulation, solar gains modeling and model-based control of shading/lighting systems. This case can satisfy both accuracy and computational speed requirements for most cases. When extremely detailed calculations of projected sunlight patterns (through and between blinds) are required (or for extremely accurate static photorealistic images), a finer grid and analysis should be used –similar to Radiance, Daysim or equivalent tools.

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# DIAGRIDS, THE NEW STABLITY SYSTEM: COMBINING ARCHITECTURE WITH ENGINEERING

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**Abstract**

Diagonalized grid structures – "diagrids" - have emerged as one of the most innovative and adaptable approaches to structuring buildings in this millennium. Variations of the diagrid system have evolved to the point of making its use non exclusive to the tall building. Diagrid construction is also to be found in a range of innovative mid rise steel projects. This paper will examine developments in the recent history of diagrid buildings to include the design, detailing, fabrication and erection issues.

The structural and architectural design of diagrid buildings falls cleanly between the typical education or experience of the architect and engineer. The approach to the current study and design of diagrid buildings is very different if looked at through the eyes of the Architect vs. Engineer vs. Fabricator/erector. The decision to express or conceal the structure impacts the design of the building in very unique ways given the angular nature of this new geometry. It is the intention of this paper to provide a comparative understanding of the design requirements and detailing of these structures via an examination of significant recent examples.

**Keywords**

Steel, Diagrid, Stability Systems, Architecturally Exposed Structural Steel

## INTRODUCTION

The evolution of the form and expression of the tall building is only slightly more than 100 years old. As a building type it has been the subject of much debate, in terms of its structure, materiality, form and environmental impact. Early tall buildings typically relied on an all steel structure based on a portal frame with reinforced connections to resist wind and other lateral loads. Later structures separated the gravity and lateral loading systems, using additional bracing in the form of overlaid diagonals, to take the lateral loads.

The design of the structural stability system of early tall buildings was clearly the job of the Engineer. Architects responded with façade designs that reflected trends of the period. Early curtain wall design typically used glazed terra cotta tiles with punched (operable) windows. With the invention of aluminum curtain wall systems, these were replaced with significantly higher proportions of glazing. No matter what the interior structural system, the façade design was based on a rectilinear aesthetic. Architecturally these towers tended towards a visual “sameness” as they were optimized and constructed across booming North American cities.

As building heights were increased and subjected to higher wind loads, new types of bracing systems were needed to reinforce the structure which in simple terms had to perform as a very tall cantilever. Where moment resisting beam to column connections were insufficient, K and X bracing was added. This was typically located internally, near the core, in order to make it as unobtrusive as possible; i.e. having no impact on the design of the façade or the flow of traffic in the building. As requirements for mechanical systems increased, these were often relegated to designated floors at intervals over the height of the building. Truss structures were used at these floors as a stabilization method. From a design perspective, these truss-band floors could easily be incorporated into the façade planning, while still supporting the use of a standard curtain wall. It was only with the design of the iconic 100 storey John Hancock Building in Chicago in the late 1960s, and the introduction of braced tubes, were Architects challenged to incorporate the bracing into their façade designs, thereby pushing an engineering choice into the architectural design.

## FROM DIAGONALIZED TUBE TO DIAGRID

Although the first building to use a diagrid was constructed around 1965 in Pittsburgh, the method was not really used again until several high profile projects were in their design phase around the year 2000. The IBM Building integrated the diagrid with the glazing system resulting in oddly shaped windows. This would have created a far more expensive option than the balance of curtain wall clad office buildings of the same period, and was likely the reason for its brief use.

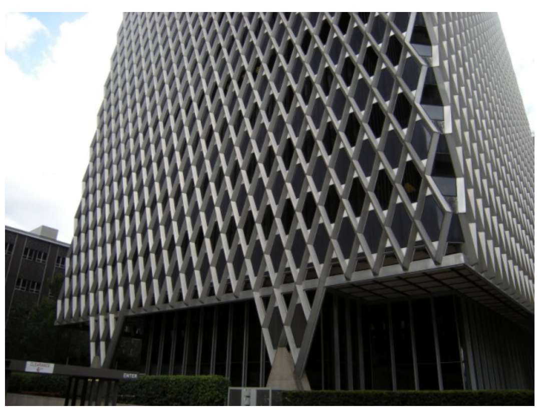

Fig. 1: The IBM Building in Pittsburgh (now called United Steelworkers Building), designed by Curtis and Davis and engineered by Leslie Robertson, is the first example of a steel diagrid expressed in a façade.[1] The steel diagrid exoskeleton assists in stability and is not a classic curtain wall system.

The primary idea behind the development of the diagrid system was the recognition of the savings possible in the removal of (most of) the vertical columns. The vertical columns were only engineered to carry gravity loads and were incapable of providing lateral stability. The diagonal grid, if properly spaced, was capable of assuming all of the gravity loads as well as providing lateral stability due to its triangular configuration. As the exterior diagrid tube is comprised of diamond shapes, triangulation is achieved where the floor edge beams tie into the grid.

> "Compared with conventional framed tubular structures without diagonals, diagrid structures are much more effective in minimizing shear deformation because they carry shear by axial action of the diagonal members, while conventional framed tubular structures carry shear by the bending of the vertical columns."[2]

Where the original diagonal bracing members were laid over a regularly framed exterior support system as a *supplementary* method of support, the current (standard high rise) diagrid system uses an exterior frame comprised exclusively of diagonal members as the *primary* means of support. If properly engineered, such systems can use less steel than conventionally framed tall buildings.[3] Where early conventionally framed office towers did not necessarily strive for a column free interior, most diagrid towers work towards the elimination of columns between the exterior structure and the core. This supports a sustainability-motivated move towards increased daylight effectiveness and LEED™ credits. This supports the choice of the structural diagrid by the Architect over the Engineer.

A diagrid tower is modeled as a vertical cantilever. The size of the diagonal grid is determined by dividing the height of the tower into a series of modules. Numerous studies have been conducted towards the optimization of the module size as a function of the building height and angles of the inclined members.[4] Normally the height of the base module of the diamond grid will extend over several stories. In this way the beams that define the edge of the floors can frame into the diagonal members providing both connection to the core, support for the floor edge beams, and stiffness to the unsupported length of the diagonal member. As a significant portion of the expense of the structure lies in the fabrication of the nodes versus the steel that comprises the diagonal element, efforts are towards minimizing their frequency and simplifying the connection between the node and the diagonal to speed up erection.

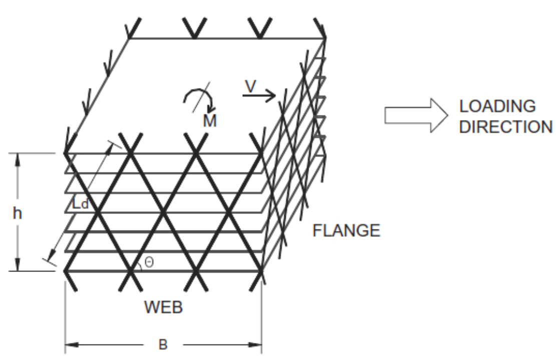


Fig. 2: Current exploration into the best geometry for diagrids is based on this Figure as established by Kyoung Sun Moon from Yale University in his research.[5]

## SELECTING THE MODULE

Much engineering research is underway to establish the optimal module size, which directly impacts the “shape” of the diagrid, window size and placement as well as the amount of resources used in the project. The impact of “shape” is viewed differently by Architects and Engineers – structural concerns also being impacted by wind and vortex shedding issues.

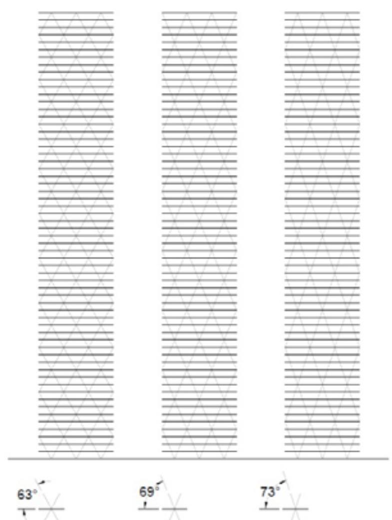


Fig. 3: This sample study done of a 60 storey tall building, based on a 1:6 ratio, measuring 36m x 36m with an 18m x 18m gravity core at the center with floor to floor heights of 3.9m confirmed 69$^o$ as the most effective angle for a uniform diagrid.[6] This value changes as a function of the building height as well as its width to height ratio.

As a tall building functions as a vertical cantilever, the taller and more slender the building, the greater will be the differentiation between the function of the diagrid elements at the base to those towards the top. This has suggested that a variation in the inclination angle of the diagonals can be used to reduce the amount of steel and provide needed resistance in the structure. The members and connections at the base of the building must be designed to resist moment while those at the top to resist shear.

The triangulation of the diagrid “tube” itself is not sufficient to achieve full rigidity in the structure. Ring beams at the floor edges are normally tied into the diagrid to integrate the structural action into a coherent tube and connect the same to the floors, and back to the core. As there are normally multiple floors intersecting with each long diagonal of the grid, these intersections will occur at the nodes as well as at several instances along the diagonal. The angle of the diagonals allows for a natural and direct flow of loads through the structure and down to the foundation of the building.

Where orthogonally framed towers conformed to International Style architecture of the times, diagrids have challenged the norm and are creating new expressions that question standard methods of design and construction. Although structural optimization might be central to discussions from the engineering perspective, many high profile constructed diagrid towers bear little similarity to optimization diagrams which would suggest architecturally driven influence.

The size of the diagrid is normally expressed in the cladding of the building. The modularity of the curtain wall will usually scale down the dimensions of the diamonds or triangulated shapes to suit the height of the floors and requirements for both fixed and operable windows. The decision to use a triangulated versus rectilinear curtain wall system is not consistent because it is a function of the overall size of the diagrid structure as well as the form of the building itself. Buildings whose diagrids support more curvilinear forms tend to use triangulated windows as these more easily adapt to the shape. Larger diagrids have less impact on the façade and can more easily accommodate standard rectilinear based curtain wall systems that may fit within the diagrid. The choice to express the location of the structural diagrid in the curtain wall varies from project to project. This is driven by the architecture and not the engineering.

Fig. 4: Capital Gate, Abu Dhabi (left) has a small module and uses a triangular window system that accommodates operable windows. Aldar HQ, Abu Dhabi (center) has a larger module and also employs a triangular system. Bow Encana, Calgary (right) has the largest module and the faceting of the structure allows for the use of a rectilinear glazing system.

## CONSTRUCTABILITY

As with any deviation from standard framing techniques, constructability is an important issue in diagrid structures. Both the engineering and fabrication of the joints are more complex than for an orthogonal structure incurring additional costs. The precision of the geometry of the connection nodes is critical, so it is advantageous to maximize shop fabrication to reduce difficulties associated with site work and erection of the odd geometries associated with the design of the nodes.

There are two schools of thought as to the rigidity of the construction of the nodes themselves. In theory, if designing a purely triangulated 'truss like' structure, the center of the node need not be rigid and be can constructed as a hinge or pin connection. Where this may work well for symmetrical structures having well balanced loads, eccentrically loaded structures will need some rigidity in the node to assist in self support during the construction process. In many of the diagrid projects constructed to date, the nodes have been prefabricated in the shop as rigid elements allowing for incoming straight members to be either bolted or welded on site, more easily, and without need of temporary supports until the next node is attached. As this type of structure is more expensive to fabricate, cost savings are to be realized if there is a high degree of repetition in the design and fabrication of the nodes. Reductions in site labor also lowers cost and time.

If the structure is to be clad or concealed, as in the case of the Hearst Tower, the diagrid elements can be bolted on site for speed of erection. In cases where the diagrid is able to be left architecturally exposed, the connections have been welded. This adds significantly to the cost of erection as more scaffolding is required for welders to access the nodes. It is more difficult to get high quality site welds due to access angles.

Fig. 5: The nodes on the Bow Encana are of two types. The diagrid on the south façade (left) is expressed as part of the double façade atrium and has been designed to AESS4 standards.[7] The node-to-diagonal connections were welded. The diagrid on the north façade (right) is concealed so although the connections have also been welded, the system is constructed of different section types and to a Standard Structural Steel level of finish.

## THE POSSIBILITIES OF DIAGRID SYSTEMS

Where early applications of expressed diagonal bracing tended not to significantly modify the basic rectilinear shape of the tower, current applications of the diagrid are exploiting the ability of the triangulated “mesh” to more easily distort and create both curved and more random geometric forms. The term “mesh” makes direct reference to the mapping techniques of 3-D modeling software and the means to make fairly direct translations from design investigations and through BIM to fabrication detailing software. The more striking examples also tend to strive for effective daylighting and use a small floor plate. This works well with the diagrid typology as the intention of the system is to eliminate interior columns between the exterior wall and the core.

Diagrid based buildings began to appear in contemporary steel design around the year 2003. All three of the initial examples – London GLA, Swiss Re and the Hearst Tower – were in development in the offices of Foster+Partners at the same time and the engineering expertise of ARUP was part of all of the projects. Interestingly, all three make use of unique variations of the system by virtue of their three dimensional geometry. The Hearst Tower is perhaps the most normalized given the rectangular shape of the tower – modified slightly as the corners are indented in places. The Swiss Re tower alters the design by creating a building that is not a cylinder but whose shape bulges at mid-height and tapers to a virtual point at the top (hence its nickname, Gherkin). Both Hearst and Swiss Re have eliminated vertical columns, create a column-free interior and use the diagrid as the primary stability system.

Where recent Supertall buildings such as the Burj Khalifa and the proposed Jeddah and China Broad Group towers increase the size of the building base to resist moment, most diagrid towers have not. Some, such as Swiss Re and Guangzhou IFC have even narrowed the base and relied on the diagrid for stability. The geometric explorations and structural success of Swiss Re as an early example of the diagrid type has served to fuel the imagination and ambitions of subsequent designs – most notably Capital Gate with its $18^{o}$ backwards lean (Fig. 6).

What is incredibly intriguing with diagrids as opposed to previous Modernist structural strategies for tall buildings is that a “basic” typology does not exist. Unlike the skyscraper designs that reflected the International Style or Modern Movement, contemporary diagrid buildings all strive to be unique, reinforcing the idea that the architectural ambitions are pushing the engineering technology in these structures. Whether in terms of height, shape/profile, node design or the length of the diagrid member, each and every diagrid structure is very different, *almost in defiance of current research looking for optimization.* This can likely be attributed to advances in computing and modeling that have run parallel to their development, if not slightly ahead, easily supporting curvilinear geometries from structural design through to detailing, the creation of shop drawings and fabrication.

## RECENT ARCHITECTURAL APPLICATIONS OF THE DIAGRID

Currently the most challenging use of the diagrid structural model is in the creation of “twisted forms”. These can be seen in numerous tall buildings presently under construction, particularly in Asia and the Middle East. The steel diagrid, in its ability to create a “mesh” is capable of conforming to almost any shape that can be created using modern 3-D modeling software. The diamond shaped grids are easily further subdivided into triangulated patterns for curtain wall manufacture. Typically the building will try to use a substantial vertical concrete core that can provide straight run elevator access through the building, and arrange the offsets to hang from the core. This requires extra engineering to ascertain the structural integrity of the building. There is also a substantial increase in fabrication and erection cost as a result of the decrease in repetitive design of the nodes.

Capital Gate by RMJM Architects in Abu Dhabi uses the strength of the diagrid to create an $18^{o}$ backwards lean on the tower. The importance of the concrete core in stabilizing the building is quite different than is required by other diagrid towers whose geometry is more symmetrical in its loading. Here the base module of the diagrid has been reduced to two floors (from the usual 6 to 8) to increase the stiffness of the tube.

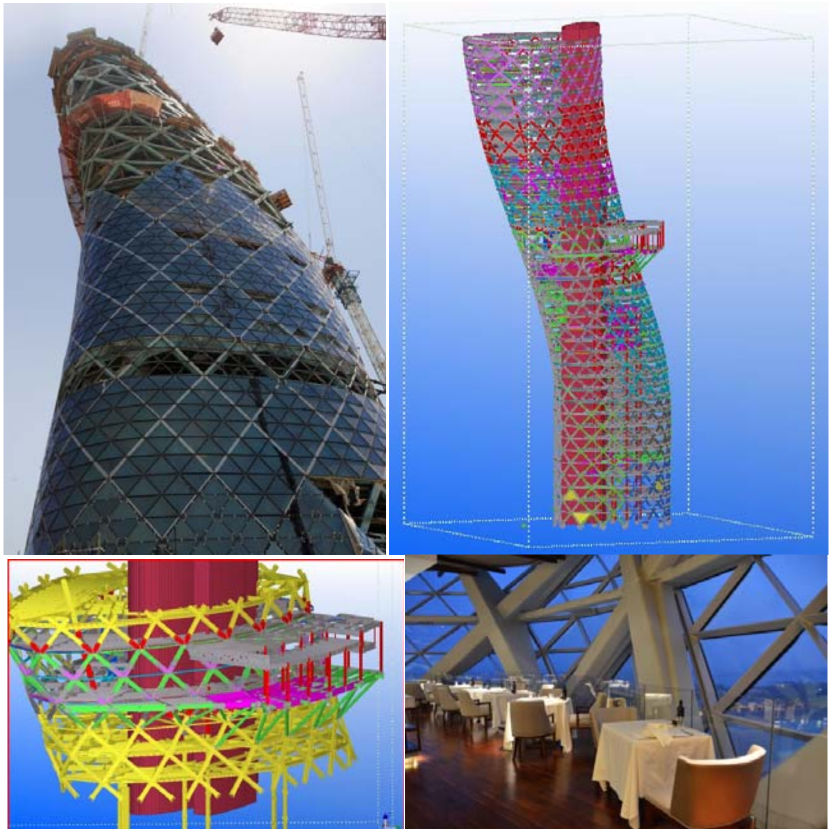

Fig. 6: Capital Gate: The construction of the tower (top left)[8]; Tekla diagram of the entire tower revealing the concrete core (top right)[9]; Tekla drawing of the structure at the $18^{th}$ floor, restaurant level and pool projection on the $19^{th}$ floor (bottom left)[10]; interior view of the restaurant on the $18^{th}$ floor illustrating the presence of the architecturally exposed welded steel diagrid frame.

As the top half of the tower is used as a hotel, operable windows have been incorporated into the triangular pattern. Where the overall scale of building gives the impression of multiple curves, this has actually been resolved through the use of triangulation into straight elements. Each diagrid has been resolved into a custom triangular steel window frame that is tied back to the diagrid and supports the glazing modules. Fire regulations in the UAE have permitted the exposure of the steel on the interior through the use of an intumescent coating. Guangzhou IFC also uses exposed intumescent coated steel. Exposure has permitted a remarkable experience of the diagrid on the interior of the building. These regulations vary greatly by jurisdiction so it is necessary to ascertain local fire regulations before designing for architecturally exposed structural steel.

Aldar HQ in Abu Dhabi (Fig. 7) is able to use the larger 8 floor base module, which is capable of forming to the curves required by the circular disk design of the tower. Again a concrete core is used, although in this case the building is quite symmetrical and so not for obvious reasons of stability due to eccentric loading.

What becomes increasingly apparent is the critical role that developments in BIM and specialized steel detailing software have played in these structures. While not making the task simple by any means, the software does allow the fabricator to extract each connection detail as a unique drawing in order to create shop drawings for fabrication. Given the incorporation of requirements for thermal expansion and movement due to temporary eccentric loading during construction, it is reasonable to expect that the final structure be identical to the drawings. In fact it must be or the pieces will not fit. Diagrids are constructed to considerably tighter tolerances than Standard Structural Steel.

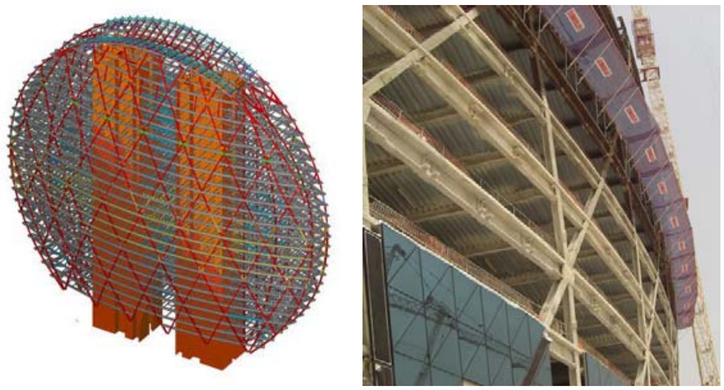

Fig. 7: Aldar HQ: The Tekla BIM model showing the pair of concrete cores and steel diagrid (left); a construction image showing the way the floors tie into the diagonals of the grid as well as the spray fireproofing (right).[11] The triangular glazing modules are also evident. Although UAE Fire codes permit exposing the steel, the tenant desired an alternate fit out and finish on the interior. The grid is nonetheless clearly expressed on the façade so an important part of the architectural expression of the structure.

Fig. 8: A comparison of the detail drawing and final structure illustrating the similarities.[12]

Detailing software played a significant role in the design of the diagrid elements for the Addition to the Royal Ontario Museum by Daniel Libeskind (Fig. 8). Although angular crystalline forms like the ROM use the principles of diagrid construction – those being taking the load path on an angle as a means to eliminate vertical columns and solve bracing issues at the same time – their structural resolution is quite different from diagrids used in towers or other more regular forms. To date most crystalline applications of the diagrid have been used to create larger aggregated volumes, often with complicated intersections of their volumes. This has meant that much of the expression and formal impact of the angular steel supports can be seen on the interior of the building. Eccentricities and large cantilevers also require more strength in the nodal connections. In order for these structures to be self supporting during construction, either temporary support towers or cable stays are necessary before the concrete floor systems are poured to provide the necessary diaphragm action.

## DIAGRID RESEARCH AND FUTURE POTENTIAL

Diagrid stability systems hold great potential for future buildings that wish to *merge Architecture and Engineering* in a compelling way as their execution, as described in this paper, requires a carefully integrated design process due to the impact of the geometry of this structural system on the spaces within the building as well as the façade and fenestration design. However, little in the way of prescriptive or proscriptive material has been published to date that might assist Architects or Engineers in the task. The majority of the published research has been conducted within the University setting (Ref. 2, 4, 5, 6) and has focused primarily on *idealized optimization*, leaving the applied *realities* of the practising professionals, hidden or internalized. Professionals involved in built projects tend to internalize their detailed findings in support of their specialization in this emerging methodology. This is likely understandable given the newness of diagrid design and the competitive global economic climate. Most significant published engineering papers on diagrids are included in the references for this paper. To date a comprehensive text has not been published. It is the intention of this author to publish such a text or handbook based on detailed personal visits and investigations of a wide range of built diagrid projects.[13]

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# EVIDENCE-BASED ASSESSMENT OF GEOMETRICAL STAIRCASE CONFIGURATIONS FOR OLDER ADULTS

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## ABSTRACT

Maintaining safety for older adults aged 65 years and older is a challenge that could be addressed by applying conscious design. Accordingly, the concept of creating a home environment which enhances safety for older adults becomes essential. Considering that staircases vary widely in their geometrical configurations, this paper presents an evidence-based assessment for geometrical staircase configurations from the perspective of reducing the risk of falling for older adults. The methodology is divided into two stages: 1) identifying the most common geometrical home staircase configurations, which include U-shape stairs, quarter turn stairs, straight stairs with landing, straight stairs without landing, helical stairs, spiral stairs, and composite stairs; 2) investigating the associated risk of falling for each geometrical staircase configuration through developing an evidence-based comparison for the proposed geometrical staircase configurations. The output of this paper is a hierarchical listing for geometrical staircase configurations which is arranged from lowest to highest reduction in risk of falling for older adults.

**Keywords:** staircase geometry, home design, older adults, falling

## INTRODUCTION

In Canada, older adults are expected to reach one-fifth of the total population over the next 20 years. Additionally, over 90% of older adults prefer to age independently in their own homes rather than move into continuing-care retirement communities or other assisted living facilities (Turcotte and Schellenberg 2007). This trend increases the need to create a home environment that enhances safety for older adults. Stairs, as part of the home environment, have been found to be associated with a higher risk of falling. In the home environment, 26% of older adults experience falls while climbing the stairs (Scott et al. 2005). One reason is due to its natural design as combinations of elevated steps that connect different floors in the home (Templer 1992). Within the home environment, falling on the stairs accounts for 25% of falling causes compared to other areas in the home (Scott et al. 2005).

Previous studies have investigated the risk of falling associated with some geometrical staircase configurations. For example, the inconsistency of stair steps was found to increase the risk of falling for older adults (Haslam and Stubbs 2006; Templer 1992);

however, the concept of linking that inconsistency to a specific stair configuration, such as composite stairs, was lacking. Therefore, this paper presents a complete integrated assessment for various stair geometrical configurations from the perspective of reducing the risk of falling for older adults. First, a history of stair development is provided then three categories are reported; subsequently, these categories are subdivided into a number of stair types that express geometrical configuration variations. Then the associated risk of falling for each staircase type is investigated through an evidence-based comparison based on previous studies. A hierarchical list for the proposed geometrical staircase configuration is developed. This hierarchical list could work as a manual for architects to prioritize geometrical staircase configurations from the perspective of reducing the risk of falling for older adults.

## HISTORY OF STAIR DESIGN

A challenge regarding stair design is the wide variation in geometrical staircase configurations, which have been generated gradually throughout the history of humanity. Throughout history, people have used stairs as a movement element toward a higher virtual or tangible point in space. The concept of using stairs to reach a virtual point was clear since ancient civilization; the pyramid of Zoser, Egypt, 2750 B.C.E is known as one of the first buildings that modeled the conceptual approach of using stairs as a "formation" of movement toward the after death world, a concept that was urbanized later for the Giza pyramids (2680-2560 B.C.E) (Helmy 2004; Roth 2007). The same concept has been found in the Mayan pyramid-temple (or the Citadel), Mexico, the traditional form of exterior stairs toward an elevated central point has been used to emphasize the place of praying and sacrificing (Filer 2005; Glassman and Anaya 2011). Ancient stairs have been used as a functional element in houses and other related facilities. In Egyptian, Greek, and Roman architecture, stairs have appeared in the dwelling as a connection between the ground floor and the roof in its regular shape (Roth 2007). Stairs in ancient years were found to be functional: straight stairs that were attached to the wall, with or without handrails (Roth 2007).

Stairs have taken various geometrical configurations in houses such as straight shaped stairs, helical shaped stairs, and composite shaped stairs. Straight functional stairs were one of the most important elements in introducing functional linearity in modern architecture, emphasizing the rule of "less is more", as attributed to Ludwig Mies van der Rohe (Robertson 1952; Roth 2007). Stairs have been inspirational focal points that provide a distinctive theme to a building, which appears clearly through the concept of helical stair design. Helical stairs were one of the most remarkable elements at the end of the Renaissance period, and in the Baroque period, they appeared in palaces as a focal point emphasizing the artistic direction of stair formation, such as those observed in Barberini Palace, Rome in 1638 (Templer 1992a). Composite stairs have appeared in both historical and modern buildings, as they provide both design flexibility and an artistic value that could be suitable for different spaces in the home.

## GEOMETRICAL STAIRCASE CONFIGURATION ASSESSMENT

In this paper, the geometrical staircase configurations are divided into three primary categories: 1) straight stairs; 2) circular stairs; and 3) composite stairs. The categorization follows the logical division developed throughout history (Roth 2007; Templer 1992a). To facilitate the geometrical staircase configuration assessment, each primary category has been subdivided into a number of stair scenarios that express the variability in geometrical staircase configurations (Bangash and Bangash 1999; Beneke 1997; Templer 1992a), as illustrated in Figure 1.

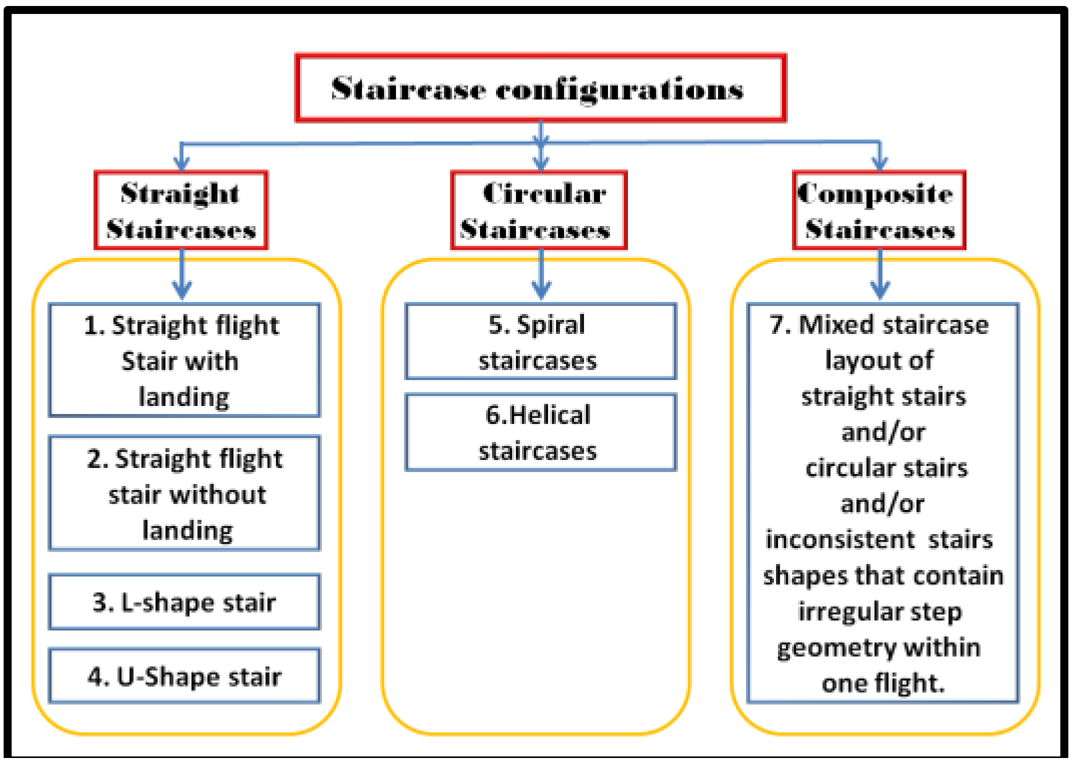
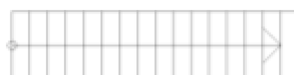
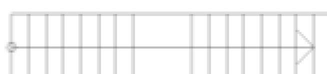
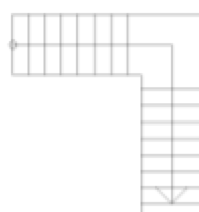
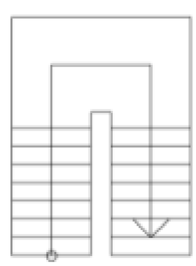



**Figure 1.** A flow chart for geometrical staircase configurations divisions.

- Straight flight stairs can be presented through four subdivisions (Bangash and Bangash 1999; Beneke 1997) as listed:
  1. Straight stairs without landing, which is formed by one continuous flight that connects two floors without a landing throughout the flight, illustrated in Figure 2.
  2. Straight stairs with landing, which are formed by one continuous flight connecting two floors and containing a landing anywhere within the flight, illustrated in Figure 2.
  3. L-shape stairs are formed by two perpendicular flights connected by a quarter turn landing; the entire staircase is used to connect two floors, as shown in Figure 2.
  4. U-shape stairs connect two floors and are formed by two flights from opposite directions that are connected with one landing between them, as illustrated in Figure 2.

- Circular flight stairs are formed by circular flights. Two subdivisions of circular stairs are as follows (Bangash and Bangash 1999):
  1. Spiral stairs are a circular set of steps formed by one flight direction, which are connected by a central pole. The spiral stairs connect two floors and do not contain a landing, as illustrated in Figure 2.
  2. Helical stairs are a circular set of steps formed by one flight direction, which do not contain a pole in the middle of the stairs. The helical stairs connect two floors and do not contain a landing within the staircase.
- Composite stairs contain a mix of straight and circular flights, or a minimum of one inconsistent step dimension. Under this category, winders are included as composite stairs. Different composite staircases are illustrated in Figure 2.

| **Staircase configurations** | **plan** | **Perspective view** |
|---|---|---|
| **(1)**<br>**Straight stairs without landing** |  |  |
| **(2)**<br>**Straight stairs with landing** |  |  |
| **(3)**<br>**L-shape stairs** |  |  |
| **(4)**<br>**U-shape stairs** |  |  |

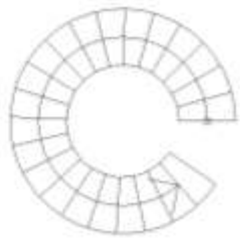
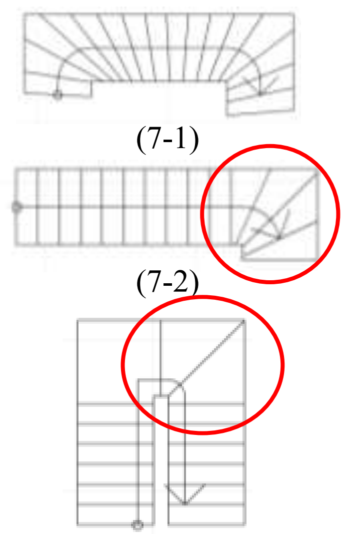
| | | |
|---|---|---|
| **(5)**<br>**Spiral stairs** |  |  |
| **(6)**<br>**Helical stairs** |  |  |
| **(7)**<br>**Composite stairs**<br><br>Examples:<br>(7-1) inconsistency of step dimensions throughout the staircase,<br>(7-2) mixed straight and inconsistency of last few steps within one flight,<br>(7-3) winder staircase. |  |  |

**Figure 2.** Proposed types of stairs geometrical configurations.

**Assessment of geometrical staircase configuration for falls prevention**

An approach to reducing the risk of falling for older adults requires an evidence-based assessment of the previously proposed staircase geometrical configurations. This approach involves, first comparing the three primary categories (straight, circular, and composite stairs), second comparing the proposed staircase scenarios for each category (see Figure 1). To set that comparison, the same floor height is assumed in order to compare various types of geometrical staircase configurations. Also, the clockwise and anticlockwise direction is neglected in this paper, assuming that older adults are familiar with using the stairs (Miyasike-daSilva et al. 2011).

**Assessment of composite stairs versus circular and straight stairs**

From the perspective of reducing the risk of falling for older adults throughout the stairs' geometrical configuration, composite stairs propose the worst design when compared to circular and straight stairs for the following reasons: 1) Inconsistent dimensions of the first 3 steps, as demonstrated by composite stairs, highly increase the risk of falling for older adults (Lee and Chou 2007; Wild et al. 1981). 2) The mixed step combination found in composite stairs, including wider stairs as a special case, also increase the risk of falling for older adults, as the inconsistent step dimensions create irregular gait patterns which increase the possibility of falling (Haslam and Stubbs 2006; Lord et al. 2001; Templer 1992). In summary, any irregularity throughout the stairs, which is recognized by composite stairs, has been found to increase irregularity in gait pattern, which increases the risk of missing steps while ascending or descending the stairs and, consequently, increases the risk of falling. However, regular staircase geometry, which is delivered by circular or straight stairs, are recommended to reduce the risk of falling (Haslam and Stubbs 2006; Lord et al. 2001; Templer 1992).

**Assessment of straight stairs versus circular stairs**

No previous record has compared straight and circular stairs. However this comparison can be set based on a study by VandenBussche et al. (2011). This study investigated the gait pattern created though the oblique stairs and its effect on the risk of falling. This study found that moving along oblique geometrical stairs was associated with higher risk than straight geometrical stairs (VandenBussche et al. 2011), as the geometrical oblique configuration creates an irregular gait pattern, as illustrated in Figure 3(a). The same measurement was applied to circular stairs, which creates the closest gait pattern to that observed on oblique stairs, as illustrated in figure 3(b). It is concluded that the straight geometrical stairs participate more than the circular geometrical stairs in reducing risk for older adults, as it offers regular gait pattern, as illustrated in Figure 3(c).

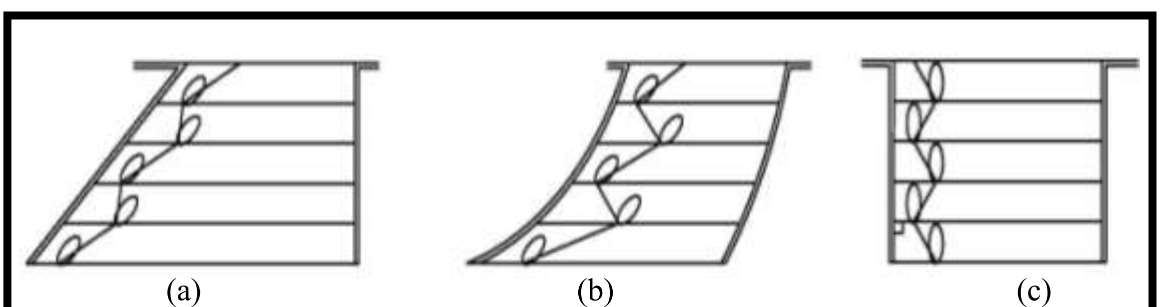



**Figure 3.** Schematic plan illustrates the gait analysis of (a) oblique stairs, (b) circular stairs, and (c) straight stairs.

**Circular stair assessment: helical stairs versus spiral stairs**

A geometric analytical approach is being considered to assess the helical versus spiral stairs regarding their effect on risk reduction. Figure 4 presents the geometrical configurations of both helical and spiral stairs. Appropriate foot placement is one of the critical assessments that contributes to reducing the risk of falling (Haslam and Stubbs 2006; Templer 1992). Despite the similarities between both stair types, unlike spiral stairs, helical stairs deliver an appropriate foot placement along the entire staircase geometry, as illustrated in Figure 4, which results in a lower risk of falling. As illustrated in Figure 4(a), the angle “x” created by the geometry of spiral stairs is very small to allow an appropriate foot placement; however, as illustrated in Figure 4(b), angle “y” created by the geometry of the helical stairs allows an appropriate foot placement.

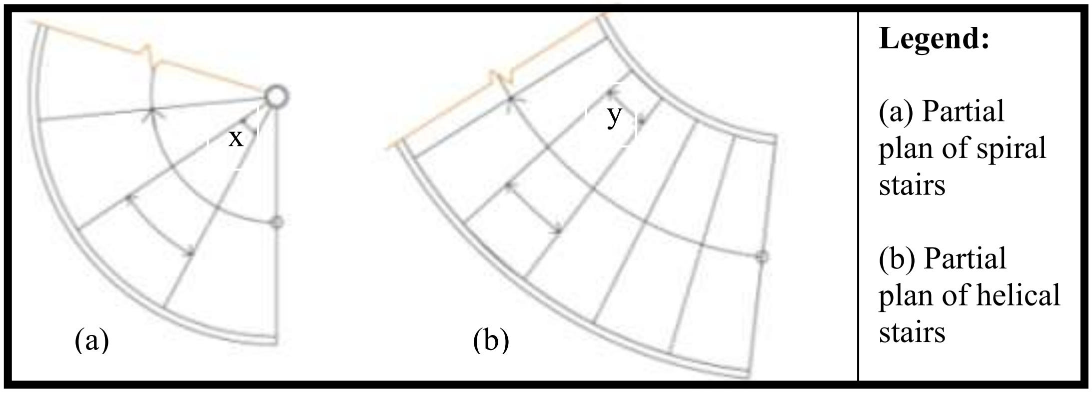



**Figure 4.** The geometrical configurations of spiral stairs versus helical stairs.

**Straight stair assessment: straight stairs without a landing versus other types of straight stairs**

Straight stairs without a landing are considered the worst geometrical staircase configuration compared to other straight stair types (L-shape, U-shape, and straight stairs with landing). A straight stair configuration without a landing has a very long flight, illustrated in Figure 2, which do not allow older adults to rest while ascending or descending the stairs. Specifically, not providing a rest area within the stairs has been found to increase the risk of falling for older adults (Covinsky et al. 2009; Templer 1992). Therefore, in the proposed hierarchical list, straight stairs without a landing is considers to be associated with the highest risk of falling comparing to other straight stair types.

**Straight stair assessment: straight stairs with landing versus U-Shape and L-shape stairs**

Although straight stairs with landings and U-shape and L-shape stairs contain landings that allow older adults to rest when ascending or descending the stairs, U-shape and L-shape stairs are associated with a lower risk of falling than straight stairs with a landing (Svanstrom 1974; Templer 1992). This difference in risk is due to the differing geometry between U-shape and L-shape stairs versus straight stairs with a landing; in the case of U-shape stairs, its 180° angle; and in case of L-shape stairs, its 90° angle; however straight stairs with landings have one direction which does not change (0° angle) (see Figure 2). Changing the direction of the staircase, as is the case in U-shape and L-shape stairs, has been found to break the visual illusion of long and steep stairs that is created by straight stairs with a landing, which allows a mental rest for older adults when climbing the stairs (Williams and RHS 1995).

**Straight stairs assessment: U-shape stairs versus L-shape stairs**

Upon comparison, the geometrical difference between U-shape and L-shape stairs is the angle of the stairs' directions; 180° for U-shape and 90° for L-shape stairs. This angle creates different landing configurations for both sets of stairs: a long rectangular landing for U-shape stairs and a square landing for L-shape stairs which equals half of the rectangular landing of U-shape stairs. As a result of this differing geometry, U-shape stairs are recommended as the best geometrical staircase configuration to reduce the risk of falling (Svanstrom 1974; Templer 1992), as they have a long rectangular landing that allows a more appropriate rest area for older adults.

## RESULTS

Geometrical staircase configurations could contribute in reducing the risk of falling for older adults (Haslam and Stubbs 2006; Svanstrom 1974; Templer 1992a). Based on the paper's assessment, U-shape stairs have been found to be associated with the lowest risk of falling for older adults. Conversely, composite stairs have been found to increase greatly the risk of falling for older adults. The result of the previous evidence-based assessment for the various geometrical staircase configurations presented in this paper can be listed through the following hierarchical list, arranged from highest to lowest risk reduction for falls in older adults:

1. U-shape stairs;
2. Quarter turn stairs;
3. Straight stairs with landing;
4. Straight stairs without landing;
5. Helical stairs;
6. Spiral stairs;
7. Composite stairs.

## CONCLUSION

This paper proposes an integrated evidence-based assessment for a range of geometrical staircase configurations, which aims to reduce the risk of falling for older adults. Based on this assessment a hierarchical list is provided that may be used for falls risk reduction for older adults when designing staircases. This proposed hierarchical list might also be useful for architects and interior designers when planning home modifications for older adults, through allowing them to select different staircase configurations which are associated with risk reduction and suitable for the proposed design space. Additionally, through applying the proposed hierarchical list for stairs in the home space, this approach will contribute to creating a friendly home design for older adults.

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# SUSTAINABLE INNOVATIONS IN BUILDING DESIGN: THE COURTYARD AND VERANDA CONCEPTS IN NIGERIA

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Abstract
Sustainable Architecture relates to the creation and utilization of healthy, responsive environments based on resource-efficient design principles and practices. This study examined the adaptation of the courtyard and veranda concepts in selected buildings in South-western Nigeria, in which the authors were involved as Architects at the levels of design, construction, maintenance and management. Using a case-study research approach, the paper examined elements of space efficiency and the building envelope within urban tropical environments. The selected buildings span a range of design typologies: administrative, educational, health, institutional, and multi-use facilities. They also represent projects at different stages of the design-construction-occupancy continuum. Based on the analysis of the case studies, the paper highlights problems that may inhibit design and construction innovations in a developing country like Nigeria, while suggesting recommendations that may enhance these. It therefore contributes to the theme of Sustainable Innovations in Building Design within tropical environments. The paper concludes that: confronted with the challenges of post-colonialism and globalization, built environment professionals in Nigeria require a radical re-thinking of strategies, to embrace along with climatic considerations, broader contextual issues of culture, community, economy, emergent technologies, and sustainability. In addition, approaches to the built environment and architectural engineering education should address the unique needs of the particular society they are a part of, if they are to be relevant in envisioning and shaping the desired future.

Keywords: Building design, Courtyard, Innovations, Tropical environment, Veranda

## INTRODUCTION

"Innovation" implies positive change: creativity plus implementation; putting novel ideas into practice. This may relate to a product, process, service, or idea that is new, novel, or improved; the use of a new product, service or method in industry, business or society subsequent to its creation (Jones and Saad, 2003). Although many technological innovations originated in the developed countries, this does not preclude the unique input and potentials from the developing countries (DCs). However, the current pattern of the globalisation process seems to be oblivious of the multifaceted intellectual wealth and natural resources of DCs. As Nwagwu (2005) argues, the beauty of a truly globalised world would lie in the diversity of contribution by all countries in the global arena. Scholars, practitioners and policy-makers are therefore increasingly adopting the "systemic" approach to innovation, with a greater awareness that innovation occurs within a system, where continuous interactions among the various actors play an essential role (Lundvall *et al.* 2008).

Innovative thinking, products and delivery should be central to the design, construction, and provision of the built environment, from its capital works through to the maintenance of assets. This is because the built environment, of which the construction sector is a core component, shapes the society simultaneously as people shape the built environment. The issue of innovation in building design is uniquely relevant in the context of a developing country such as Nigeria, where low levels of technological advancement, infrastructural provisions, inappropriate legislations, and obsolete regulations tend to impede innovation. Innovation may not however imply an absolute break from tradition, but rather, represent a creative improvement upon it.

This paper contributes to the theme of 'Sustainable Innovations in Building Design', focusing on selected buildings in South-western Nigeria. It examined the innovative adaptation of two traditional architectural design elements – the courtyard and veranda – in urban tropical environments, and how these may enhance space efficiency within the building envelope. It highlights some problems inhibiting design and construction innovations, while suggesting recommendations that may enhance these.

## LITERATURE REVIEW

Sustainable Architecture relates to the creation and utilization of healthy, responsive environments based on resource efficient and ecological principles and practices (Guy and Farmer, 2001). Two important criteria that may impact sustainability at the level of the building are the space efficiency and the nature of the building envelope.

### Space efficiency and the Building envelope

Space efficiency (SE) refers to the ratio of Net (usable) Floor Area (NFA) to the Gross Floor Area (GFA); and is therefore achieved by maximising these within the ambit of applicable building codes and regulations (Sev and Ozgen, 2009). A key rationale for the provision of sufficient functional spaces is to enable developers and owners to get maximum value and returns from the high cost of land (Kim and Elnimeiri, 2004). However, the floor shape also has vital implications for SE in terms of the interior space planning, layout of equipment, exterior building envelope, structural system, and the utilization of natural light and air. Designing for space efficiency implies that every space functions effectively in meeting the user-needs. Generally the more simple and regular the floor shape is, the easier it is to respond to user requirements in terms of space planning and furnishing (Sev and Ozgen, 2009).

The building envelope – the element between the internal and exterior spaces – is vital to controlling the flow of air, heat, light, or noise within a building. In recent times, technological innovation has facilitated improvements in the performance of building envelopes – including walls, roofs and fenestration components. The extreme of this trend is the notion of adaptive or responsive architecture in which building envelopes and materials can adapt their performance, in real time, to environmental changes, maximise energy, provide more occupant comfort, and better overall space efficiency (Beesley *et al*, 2006).

### Adapting the Courtyard & Bungalow-Veranda Concepts

Two notable aspects of Nigeria's traditional architecture which provide opportunities for innovations relate to (1) the courtyard system and (2) the bungalow-veranda (Osasona and Hyland, 2006).

The concept of the courtyard or 'impluvia' as a predominant layout of the built-form of traditional family compounds in Nigeria reflects the socio-cultural status of family life. This built-form enhances intensive social interaction among family members, as it is planned to simultaneously assert individual privacy while fostering group cohesion. Rooms or other basic residential units are often arranged around this central area which may vary in shape, size and characteristics depending on the nature of the elemental units, the form of construction adopted, influences of topography, historical influences on the particular culture and individual preferences. As the core of the house, the courtyard brings light and air into the center of the building, as well as a sense of outdoor living. In some cases, cooling rainwater is drawn from elaborate pitched roofs, through the courtyards, to help moderate internal air temperatures.

The courtyard is a common feature in the architectures of the major Nigerian tribes – Hausa, Yoruba, and Igbo – though with slight variations (Richardson, 2001). In Yoruba architecture, palaces and the traditional compounds of chiefs and large extended family units often contain a series of courtyards linked together by passages. In addition, the courtyard is a major feature of the aggregation of spaces and an essential component for environmental control and socio-cultural exchanges (Osasona and Hyland, 2006). Irrespective of its form or nature, the courtyard serves the function of accommodating group activities of household members and visitors. The courtyard system therefore has the potential to maximize space efficiency and enhance building envelopes in urban tropical environments.

The ***bungalow*** is a one-floor house with a large roof and overhangs. It represented a unique architecture designed to fit the tropical bio-climatic conditions, while simultaneously being a cultural construct that responded to the beliefs and desires of the colonialists. It however remains to be conserved, reused and re-designed (King, 1984). As a built-form adapted to the tropical climate, the bungalow evolved as a transformation of the peasant Bengah *banggolo*, diffused all over the then British Empire. Typically, it is a free-standing, single-family building, with central functions organized in the core and a series of wrap-around functions that insulated the house from the heat or cold. The critical wrap-around element was the veranda or transitional zone that allowed ventilation to circulate through the building while still providing shade (Lefaivre and Tzonis, 2004). An Asian tropical invention, ***the veranda*** is not only an important architectural feature, it also supports an entire lifestyle in its confines – sitting, sleeping, and socializing – while simultaneously allowing its occupants to retreat into the privacy of the inner chambers. It is a porch-like, shaded area separating inside and outside, comparable to an immaterial, virtual non-wall (Mehrotra, 2000). A variety of devices such as louvers and screens were adapted to modulate the extent of breeze allowed into the interiors, as well as to provide privacy for the veranda – resulting in a rich architectural vocabulary. Many variations of the bungalow and veranda have appeared in the tropics, defined by the cultural heritage of ethnic groups, their lifestyle and the traditional crafts of local builders.

In their original traditional contexts, the courtyard and the veranda concepts were mainly restricted to residential building typologies. The rationale for the present study is therefore to examine the innovative adaptation of these concepts to other building typologies: administrative, educational, health, institutional, and multi-use.

## RESEARCH METHOD

This case-study research approach focused on five selected buildings in South-western Nigeria, in which the authors were involved as Architects at the levels of design, construction, maintenance and management. Qualitative primary data were derived from the design and working drawings, physical observation, and photographic records. The buildings were purposively selected to span a range of design typologies: administrative, educational, health, institutional, and multi-use facilities. They also represent projects at different stages of the design-construction-occupancy continuum. The study analysed space efficiency relative to the buildings' envelopes, emphasising the innovative adaptation of the courtyard system and the bungalow-veranda concept.

## ANALYSIS OF THE CASE STUDIES

The designs of these case-studies aimed at spatially efficient building envelopes, which were achieved by keeping the buildings' shapes simple, but aesthetically and functionally pleasing. The simple shapes and envelopes lend themselves to space efficiency and functionality, which also have implications for the speed and ease of construction, and translate into direct cost savings.

1. Shopping Complex/Events Centre at Ile-Ife, Osun State, Nigeria (Figures 1 & 2)

This two-story medium-size shopping complex consists of a system of shops of various categories and sizes to be provided on rental basis. It incorporates some eateries, which are common features in this urban social context. The courtyard and veranda concepts were adapted, as many of the shops are typically accessed from verandas or corridors surrounding two courtyards. These aid natural lighting and enhance natural ventilation, especially when there is power outage. A column-free multi-purpose hall for social and recreational events adjoins the system of shops, with relatively high space efficiency.

Legend: 1. Shops 2. Courtyards 3. Eateries 4. Multi Purpose Hall
Figure 1: Ground Floor Plan of the Shopping Complex

Figure 2: Front/Right Side View

2. Health Center for Adekunle Ajasin University, Akungba-Akoko, Ondo State

The Adekunle Ajasin University, a state-owned University in Akungba Akoko, Ondo State, required the provision of a health center to serve students and staff. The facility comprises of essential functional and spatial provisions for a primary health care center, including wards, pharmacy, out-patients department, an operating theatre, and X-ray departments. The building envelope and use of courtyards were optimized to eliminate dependence on artificial lighting and ventilation (Figure 3). The proximity, visual connectivity, and access to the outdoors aimed at enhancing the users' health and well-being. The materials specified for the interior of the building envelope are low-emitting, while adequate cross-ventilation is supportive of a healthy indoor air quality. The eco-friendly environments created by the courtyards and surrounding greenery were intended to have therapeutic effects on the patients. Waiting rooms to the consulting offices were fitted with low window sills allowing patients to have unrestricted views of the landscaped courtyards, even when seated.


Figure 3: Ground Floor Plan of the Health Center

3. Office Complex for the Centre for Distance Learning (CDL), Obafemi Awolowo University, Moro, Osun State (Figures 4 & 5)

The Centre for Distance Learning of the Obafemi Awolowo University is located in Moro, a few kilometers from the main campus of the University. The center serves as a unit of the University which runs such academic activities that fall outside of the core formal faculty system. The project, which is still under construction, is an administrative building on two levels, comprising of offices, seminar and conference rooms and other administrative facilities. Efficient cross-ventilation and extensive day-lighting were achieved by the use of appropriately-sized courtyards and verandas created in the core of the building, overhangs to reduce unwanted heat gain, and other architectural shade devices. Space efficiency was enhanced through the design of loft spaces, the incorporation of multi-function spaces, and the use of built-ins.

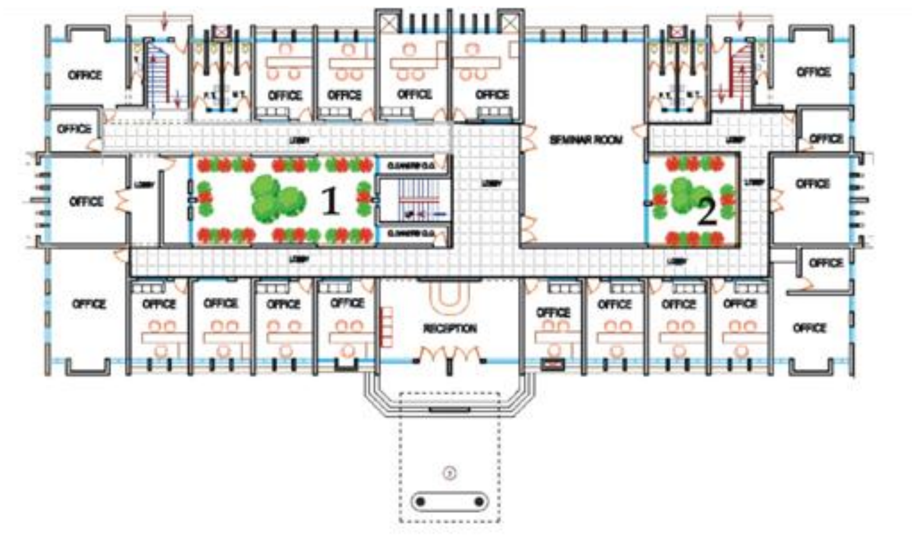


Figure 4: Ground Floor Plan of the CDL Office Complex

Figure 5: Views of Courtyards 1 & 2

4. Administrative Office Complex for the National Center for Technology Management, Obafemi Awolowo University, Ile-Ife (Figures 6 – 9)

This building consists of offices and other support facilities such as seminar rooms, board rooms, and libraries. It rests on a natural slope, which has been retained and used to create sunken courtyards, which provide shaded microclimates within the building, leading to reduced heat loads. The two paved and landscaped courtyards define a partially detached, yet integrated design, resulting in effective ventilation and lighting for virtually all the spaces, with limited dependence on artificial lighting and ventilation systems. The provision of corner offices and the articulation of the façade significantly enhanced space efficiency and quality. The form of the design was generated from a 'technological concept' – reflecting the Institution's key theme – which consists of four symmetrically arranged slanting roof planes, towering over a central core (Figure 6). From the front elevation, the building can be perceived as a single story building tapering down on four sides to a ground level floor. The frontal glazing assumed the form of 600mm curtain walling spaced with 900mm wide vertical block-wall panels tapering down in a descending order from the first to the ground floor as shown in the approach view (Figure 7). A basement was created on the rear side, due to the backwardly sloping terrain and for functional considerations to meet up with the spatial requirements of the brief. Figure 8 shows the views of the courtyard quadrangles resulting from the conceptual form of the design.

Figure 6: Views showing the slanting roof planes

Figure 7: Approach & Side Access Views

Figure 8: Courtyard Views

5. Auditorium for the Centre for Distance Learning (CDL), Obafemi Awolowo University, Ile-Ife, Osun State (Figure 9)

This auditorium was designed with a seating capacity of 500. It has adjoining satellite seminar rooms around an entrance foyer, which also accommodates conveniences, while back stage facilities exist at the rear. Even though the building is fitted with isolated air-conditioning units, a free standing concept was adopted in the design, which ensures that the facility has all sides filled with windows opening to the outside. The column-free interior enhances space efficiency. The natural daylight provided saves energy consumption through the reduced need for artificial lighting. Window placements and sizes are balanced with lighting needs for the activities taking place within the buildings. This again ensures that the building is guaranteed to function effectively even in the event of power outage. Also, eco-friendliness is displayed by an ornamented courtyard in the entrance foyer to the auditorium which also provides excellent lighting and ventilation (Figure 10). A pyramidal ceiling concept was used in the interior, to achieve a harmonious balance of aesthetic and acoustic purposes. This consists of a horizontal peripheral plane integrated with a pyramidal core to emphasize the octagonal shape of the auditorium. The ceiling is made of textured modular acoustic boards fitted in a suspended aluminium grid as shown in Figure 11. Visual interest was introduced through the interplay of three different colors in the choice of fabrics for the raked seats.

Figure 9: Approach View

Figure 10: View of Courtyard

Figure 11: View of Pyramidal Ceiling

Figure 12: Pockets of Green Islands

The structure is organically integrated with the natural terrain and the site context. As part of the external works, the right-side secondary entrance is accessed through a paved area with five (5) pockets of green islands arranged harmoniously (Figure 12).

## DISCUSSIONS

### Transiting from the Traditional

The transition of design and construction techniques from the traditional to industrialized, has been dependent on factors such as: the level of technological advancement, availability of relevant construction materials, infrastructural facilities, professional expertise and skilled labor. In developed countries, the highly functional infrastructural facilities have encouraged design approaches that could be fully dependent on artificial lighting and ventilation systems. Where such approaches have been used in developing countries, they have often met with functional failures as the infrastructures needed to sustain such designs are insufficient. In few instances where these exist, the maintenance and running costs are usually very prohibitive, leading to higher rents and asset management costs.

The case studies in this paper can be viewed as eco-friendly designs which provide the option of passive approaches such as building orientation, cross ventilation and night cooling, thus limiting the dependence on artificial systems. These are based on the innovative adaptation of the courtyard and veranda concepts, with their strong social-cultural flavor. These have however not totally excluded the use of artificial means of lighting and ventilation, but rather adopted their integration. The case-studies indicate the conscious use of architectural effects of shade and light patterns in dynamically modulating the perception and atmospheres of enclosures. The courtyard enhances air exchange rates and consequently, indoor air quality within the building envelopes.

### Factors Inhibiting Innovations

Some factors inhibiting design and construction innovations may be highlighted. Inadequate supporting Infrastructure constitutes a major limitation. With incessant power outage, excessively high costs of running power generating plants result in severe inefficiencies. While the skills for innovative designs abound, many professionals have discovered that 'innovative buildings' – if viewed only in terms of complexity and technological advancement – often end up being less functional due to limitations related to maintenance requirements and lack of resources to sustain them. Innovation may not be synonymous with complexity; simplicity may indeed be the virtue of a good innovation.

Well-intentioned building and planning regulations often severely hinder innovation. The case-studies in this paper enjoyed the benefit of being designed under less-restrictive organisational and regulatory frameworks of the Universities. The problems of clients' budgets, cost restrictions and time pressures often limit innovations. Deadlines set for design delivery may hinder the required flow of creativity needed to generate, develop, and implement innovative ideas. Climatic considerations may also limit flexibility in the choice of materials.

Organisational impediments to creativity and innovation need to be holistically addressed. Promoting strong linkages between academic communities, researchers and the industry may enhance innovation on a larger scale and produce a positive impact on the whole system, helping to diffuse innovation through the industry. This would enhance the required complementarities between academic research and industrial relationships.

## CONCLUSION

This paper explored the theme of Sustainable Innovations in Building Design through the qualitative analysis of five case studies of selected buildings in South-western Nigeria. The design approaches to the five case-studies aimed at presenting spatially efficient building envelopes. While these case-studies do not necessarily represent the most advanced examples of innovations in building design available in Nigeria, they serve the purpose of illustrating the innovative adaptations of the courtyard and veranda concepts, within the professional purview of the authors.

Confronted with the challenges of post-colonialism and globalization, built environment professionals in Nigeria require a radical re-thinking of strategies, to embrace along with climatic considerations, broader contextual issues of place, culture, community, economy, emergent technologies, and sustainability. In particular, the sustainability paradigm requires new thinking across the spectrum of human endeavour. Economic, social and institutional innovations need to keep pace with technological innovations. In addition, approaches to the built environment and architectural engineering education should address the unique needs of the particular society they are a part of, if they are to be relevant in envisioning and shaping the desired future.

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# MICROCLIMATE ANALYSES FOR THE DESIGN OF BUILDING-INTEGRATED WIND TURBINES

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Keywords: CFD, Energy, Microclimate, Turbines, Wind

## ABSTRACT

This paper presents the insights gained by analyzing the microclimate associated with local wind patterns for the design of building-integrated wind turbines (BIWT). The wind environment around buildings is difficult to accurately predict and, as a result, can cause proposed building-integrated wind turbine designs to fall short of their expected performance. The study uses Typical Meteorological Year (TMY) data to perform site-level and microclimate-level analyses using computational fluid dynamics to analyze several proposed designs for a museum in Erie, Pennsylvania and a research facility in Philadelphia, PA. This data shows the importance of in-depth microclimatic studies of a building's site and affiliated environmental factors. These analyses can be used to lead a design team towards integrated aesthetic and functional design decisions that consider the complexities of site and building geometry and their effects on urban-level wind flow. This study explores the influence of the environment surrounding a building, with regards to BIWT performance. To improve BIWT performance, it is concluded that a symbiotic relationship between architect and building scientist should be emphasized during the architectural design process through the workflow defined in the paper. This workflow enables both the architect and engineer to create a dialogue that aides in the creation of a synergistic end result. This workflow can offer site-specific insight early in the design process that is important when working towards making well-informed design decisions, as it is important to identify necessary design changes early in order to avoid incurring expensive change-orders later on in the building's construction.

## INTRODUCTION

In the United States, buildings account for more energy consumption than any other sector. According to the Department of Energy, the built environment consumes roughly 40% of the country's primary energy; other developed nations such as the UK and the European Union see similar statistics (DOE 2011) (Perez-Lombard et al. 2008). In addition to this, the majority of energy consumption in developed nations comes from within cities. While this represents a startling magnitude of dense resource consumption, it also presents a large opportunity for improvement. Because this vast quantity of energy use is originating from a single type of source, improvements within the building industry have the opportunity to have large downstream effects. An example of such an improvement includes integrating wind turbines with urban buildings as a means of creating site-generated electricity at the source of densest energy consumption. The idea is that building-integrated wind turbines will aide in decreasing building energy consumption, thereby reducing the stress on energy infrastructure and the environment. While the idea of an in-house electricity generation source is beneficial, harnessing the power of the wind within an urban context is not easily deployable.

In a previous study, it was shown that turbulence decreases the efficiency of wind turbines (Muljadi 1997). One of the complications that arise when using wind turbines in an urban context is that buildings create recirculation zones and interact with the surrounding microclimate in complex ways. This makes ideal wind flow conditions less frequent as altitude decreases. In addition to the influence of the surrounding urban morphology, buildings must consider the influence of their own geometries when integrating turbines with the design. A building's own shape creates diverse flow conditions within its microclimate that can contribute to or detract from a building's goal of generating wind energy. Gaining insight as to how a building's microclimate is influenced by the many environmental and geometric factors which define a site is a complex process. This requires insight from computational software in order to be able to predict the complex wind characteristics within the urban environment.

Traditionally, however, the architectural design process is fragmented. Within a traditional project's delivery, engineers are hired after a building is conceptualized and the opportunity for an initial scientific analysis of a site is somewhat lost. As projects move forward in time, the ability to make cost-effective changes is reduced and post-design analyses of a building's microclimate can have only a limited influence as the design moves forward, thereby reducing the likelihood that a design will be as effective as originally intended. This serially-fragmented relationship between architect and engineer presents a problem for the success of BIWT implementation. This study makes the argument that, for a building which is to take advantage of BIWT, a project workflow which allows engineers and scientists to present microclimatic analysis as a design parameter, rather than as a validation or disproval of a proposed design. This collaboration between architect and engineer would be beneficial for BIWT design as well as for the design of other building energy systems. The scope of this paper, however, will focus on building-integrated turbine design.

## METHODS

The workflow which is derived from the methodology of this study is proposed in order to create a collaborative relationship between architect and building scientist. This relationship is intended to allow the facets of the design process which are crucial to the success of BIWT design to complement one another without stifling the creativity of the architect throughout the design process. This workflow allows the engineer to support the architect with that which is necessary to make informed design decisions. This makes it such that the engineer is acting as a design informant, rather than a post-design consultant who must inherently limit and constrain the creative investment of the architect. The steps of this workflow are as follows: analyze Typical Meteorological Year (TMY) weather data to determine if the natural environment supports wind turbines, use computational fluid dynamics (CFD) to study the effects of the site's surroundings, propose a geometry based on the initial analyses, and then use CFD to analyze the proposed design in more detail. The results of this analysis are then used in a feedback loop, which is used to inform redesigns, if necessary, that will enable the architect to converge on a solution that satisfies both aesthetic and turbine-related functional goals. The workflow is outlined further in this section and is illustrated in Figure 1 below.

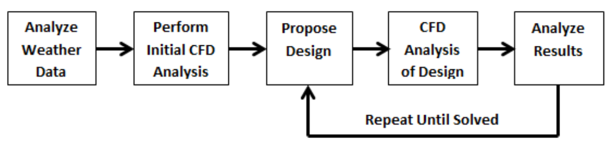



**Figure 1**. *This figure illustrates the workflow proposed in this paper.*

**Weather data**

A site's ability to support wind turbines is inarguably linked to the weather conditions of the site. The first step of the defined workflow is to analyze a site's wind patterns. Typical Meteorological Year data was used in this study in order to generate a wind power distribution as well as a wind power density for each site. Average wind power is plotted for each 22.5 degree interval as shown in Figure 2. This plot offers insight as to what the wind energy generation potential will be for a particular site. Understanding the site's wind characteristics is important when considering how a building should be configured within its location.


(a) (b)

**Figure 2.** *Plots of average wind power per m² of turbine area per hour, based on TMY data for Erie and Philadelphia in Pennsylvania*

**Site study**

Once the prevailing wind conditions for a site are determined, the site must be modeled and analyzed in order to assess the effect of the surrounding urban morphology. It has been shown in a previous study that the density of the surrounding buildings has a large effect on flow characteristics within an urban environment (Lee & Kim 2009). A major reason why BIWT are infrequently used within dense urban settings is that vortices created by adjacent buildings deteriorate the wind quality necessary for wind energy generation. Insight as to how a building's site affects the builidng's microclimate is important and can be simulated using computational fluid dynamics software (CHAM 2012). Site models are created in Google Sketchup and converted to STL files. They are imported into CFD software and converted into blockages. For the equations governing the CFD simulations, refer to "Ventilation Performance Prediction" in Building Performance Prediction (Srebric 2011). Boundary conditions can be found in Table 1. A low-level evaluation of the proposed site can then be performed to assess the influence of surrounding structures or landforms. While onsite measurements would be the most reliable source of wind data, the measurements would have to span the entire year and there is seldom enough time to perform this analysis. Because of the lack of time, CFD is used to offer insight towards a site's usability. Gaining insight as to where the urban environment creates regions of high and low velocity is important as a design input because wind power is related to the cube of velocity. If a turbine is located in a region in which the velocity is half that of another region, the available wind power is reduced by 87.5%. Because of the importance of locating turbines precisely within a complex microclimate, the engineer becomes a crucial member of the design team as the engineer's input helps to define how a building is to be shaped, as opposed to simply evaluating a design after its completion.

| | |
|---|---|
| Inlet | Size: 1,775 x 281 m for Site 1, 1,345 x 223 m for Site 2; velocity: 5.0 m/s for Site 1, 4.5 m/s for Site 2; reference height: 10 m; temperature: 21.1 $^{o}$C; turbulence intensity: 0.05; turbulence length scale: 1.6 mm |
| Outlet | Size: 1,775 x 281 m for Site 1, 1345 x 223 m for Site 2; velocity: 5.0 m/s for Site 1, 4.5 m/s for Site 2; reference height: 10 m; temperature: 21.1 $^{o}$C; turbulence intensity: 0.05; turbulence length scale: 1.6 mm |
| Ground | No slip surface conditions |
| Buildings | Solid Blockage; No slip surface conditions |

**Table 1.** *Boundary conditions for both the initial study and microclimatic study.*

**Microclimatic study**

Once the site-influenced microclimate is investigated, a detailed analysis of a building's proposed geometry is performed. The goal of this study is to evaluate the effects of the flow variations caused by the geometry proposed by the architect. Even geometries which intuitively appear to complement wind flow patterns may interact to the wind in unexpected ways, so this detailed analysis is necessary in determining how a building will perform under various conditions. This microclimatic analysis may warrant revisions to the proposed geometry. The aerodynamic shortcomings illustrated by the CFD analysis should be taken into consideration and should inform the next iteration of the design process. The building design team must then reanalyze the new microclimate created by the change in geometry.

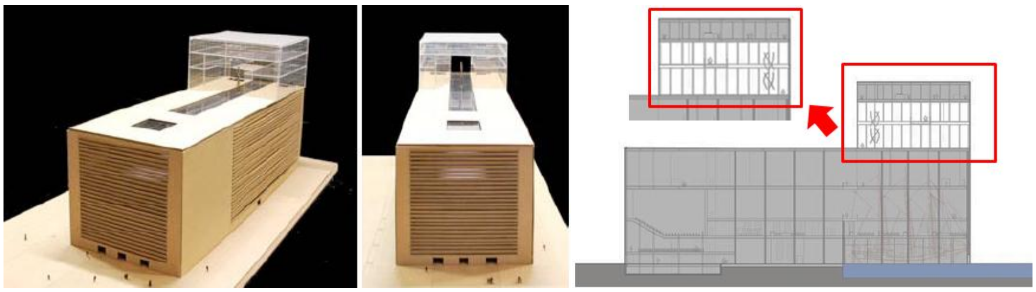
## RESULTS

In this paper, case studies are presented for two different sites, one in Erie, PA and the other in Philadelphia, PA. For each of the case studies, it is shown that the workflow developed in this paper offers insight during the design process. This insight can be used to shape and develop the aesthetics of the building-to-be-designed by validating or negating design decisions as they pertain towards the functionality of a proposed BIWT design. This workflow is an iterative process that assists the architects and engineers in converging on an optimum design. Several cases were explored in this study, the results of which are discussed below.

**Site 1**

For the first site, two initial design proposals are analyzed. In Building 1, the initial wind analysis shows that both the south and southwest wind directions prevail over the course of the year. For this site, southwest refers to 22 degrees south of west. It is shown that, for the south and southwestern wind directions, the most frequent usable wind velocity is 5 m/s. Additionally, it is found that the site's wind power density is 138.3 W/m$^2$. The most frequent usable wind condition is modeled instead of the highest velocity observed because infrequent instances of high velocity wind over the course of the year do not generate large amounts of energy across the whole year. For the second step of the workflow, both south and southwestern wind conditions are analyzed using computational fluid dynamics, showing that there is little influence from surrounding buildings that would negatively impact the site's ability to generate wind energy, given the observed prevailing wind directions.

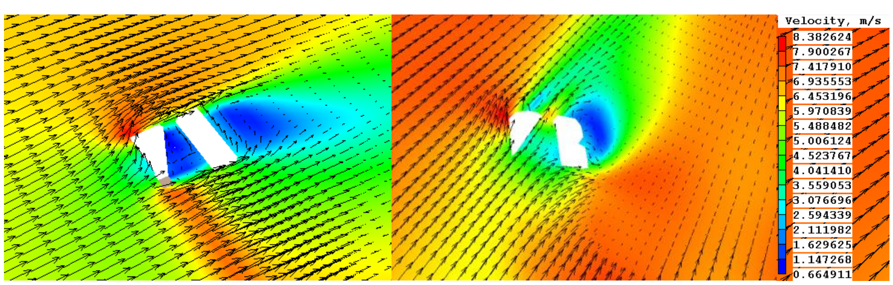
For the next step of the workflow, two potential designs were proposed for Site 1 after initial wind analyses. The first design proposed is shown in Figure 3(a) for Building 1, and encases a vertical wind turbine within functional space on the roof of the building. The turbine is initially proposed to be placed at the opening of the flow cavity with a relatively narrow wind channel opening. Because the architect has chosen to align the building's geometry with the adjacent structure, the proposed design is unable to take advantage of southwestern wind, as is shown in Figure 4(a). However, there is a higher potential to generate flow that passes through the wind funnel coming from the southern prevailing wind direction. The architect's initial wind channel geometry is relatively narrow and a large stagnation zone forms, blocking a majority of the wind flow passing through the space. Additionally, the wind which does pass through the channel is extremely turbulent, thereby reducing the efficiency of the turbine. A decision is made to modify the shape of the opening in order to create a wider channel opening, taking advantage of more powerful and less-turbulent, wind flow. This is consistent with the iterative nature of the workflow. Analysis is then performed on the redesign. This modification allows more wind to pass through the tunnel, but still creates a stagnation zone at the entrance to the channel. Additionally, due to the fact that the architect has initially chosen to place the turbine at the mouth of the wind funnel, flow conditions surrounding the turbine are not ideal due to a large amount of stagnation-induced turbulence as the incident wind collides with the wall of the funnel. Additionally, velocity through the channel is approximately 3.5 m/s, which is less than the 6 m/s that pass through the rear of the channel resulting in a wind power differential of approximately 100 $W/m^2$ of turbine area. The large difference in velocity, as well as the stagnation zone at the wind channel's entrance, is shown in Figure 4(b). Because of these results, the turbine is then proposed to be moved to the rear of the wind funnel in order to take advantage of higher velocity and steadier flow conditions as shown in Figure 3.



(a) (b)

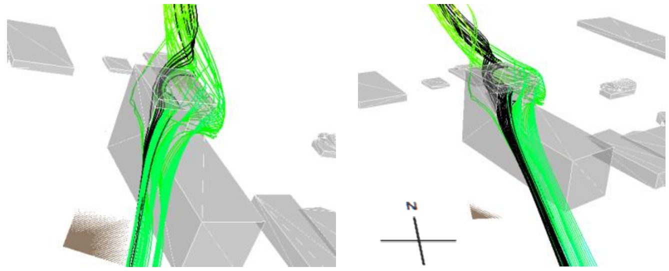
**Figure 3.** *(a) An initial BIWT design that features a vertical wind turbine within a funnel-shaped portion of the building at roof-level for the site in Erie, PA. (b)A revised BIWT design showing that the wind turbine was moved to the back of the funnel-shaped structure to take advantage of higher wind velocities for Building 1*

Figure 5 shows that flow is disrupted at the opening of the channel. A specific set of streamlines is highlighted in black to illustrate flow separation. As it currently stands, further iterations of this design are desired because the current design still only takes advantage of a narrow band of incident wind. The aforementioned stagnation zone on the northwest wall of the wind channel creates poor flow conditions throughout the channel, creating turbulent, low velocity flow at the mouth of the opening. Additionally, the region at the rear of the tunnel, in which flow reaches a high velocity, is still turbulent and unstable. This condition is not ideal for maximizing turbine efficiency, so the design must be refined further. This insight can be used to further modify the proposed design in order to optimize the functionality of the turbine design, in addition to converging on an aesthetic solution that is within the architect's vision. In this case, the architect could re-orient the wind channel in a more western direction in order to reduce the severity of the wind stagnation which happens on the east wall of the channel.




(a) (b)

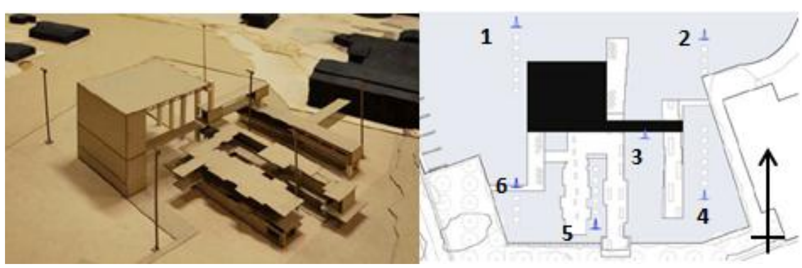
**Figure 4.** *Velocity fields from CFD studies performed for (a) the SW and (b) S wind directions around Building 1. Section is cut through wind turbine channel. Streamlines through this channel are shown in Figure 5.*




(a) (b)

**Figure 5.** *Southern streamlines through the wind channel opening for Building 1. (a) A single plane of incident wind is shown separating upon entry to the wind channel. (b)The swirling effect that the channel's geometry has on the incident wind is shown.*

In Building 2, the second design proposed for the Site 1, the architect has chosen to detach the wind turbines from the building and place them throughout the site in order to reduce some of the negative effects of the turbulence associated with mounting turbines directly on the building's structure. This is a design resulting from the initial site study. The proposed design is shown in Figure 6. This strategy generates strong flow conditions for a majority of the turbines; however, when considering the southwestern wind direction, it is observed that Turbine 2, as defined in Figure 6, resides within an unstable flow zone. While an initial analysis of flow velocity throughout the site shows that wind conditions are ideal for wind energy generation, streamline analysis illustrates that the turbine is on the fringe of a recirculation zone which is generated behind the bulk of the building's structure, as illustrated in Figure 8. Unstable flow negatively affects turbine performance, so a further revision of building geometry or turbine placement is desired in order to be able to take full advantage of the site's flow characteristics (Muljadi et al. 1997). This revision could manifest itself as a lateral movement of the turbine or by making the turbine taller in order to avoid the zone of instability.




(a) (b)

**Figure 6.** *(a)The second proposed building design for the Erie site and (b)The proposed locations for six turbines around the site*

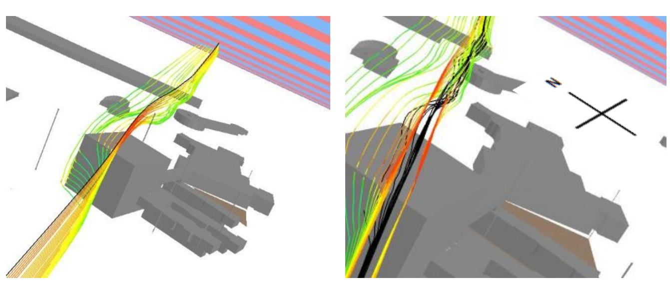


**Figure 7.** *Streamlines showing the effects of the building's geometry on a turbine located in the leeward side of the site for SW winds (Turbine 2)*

**Site 2**

For Site 2 in Philadelphia, this study investigated a retrofit project. Because of the programmatic and aesthetic limitations inherent in retrofit projects, the architect does not have much freedom in configuring the building's site situation or geometry. An initial wind study of the site showed that the predominant wind directions are from the west, south southwest, west northwest and the north, as is shown in Figure 2. Additionally, it was shown that the most frequent usable wind condition from each of these directions was approximately 4.5 m/s. The wind power density for this site was 90.8 W/m$^2$. It was immediately apparent that, even before the study took place, the western wind direction would not work due to the presence of a large building directly next to the site. This building also creates unsteady flow conditions in the south southwest and west northwest wind directions, rendering the northern wind direction the only usable prevailing wind direction, due to having relatively small buildings in line with it.

Due to the fact that this case is a retrofit of a site-constrained building, the building's holistic geometry cannot be based on the initial CFD study; however the microclimatic study can be used by the architect as a design informant when integrating the BIWT retrofit with the existing building's aesthetic. Simulations of the northern prevailing wind show that there are regions across the building's roof that experience unstable flow. Additionally, the building that is downwind and across the street causes regions of high pressure which steer wind diagonally across the eastern side of the roof plane, as shown in Figure 8. The streamlines shown in Figure 8 do, however, show some regions of the roof which experience relatively steady flow and could potentially be used to harvest wind coming from the northern direction. The specific placement of turbines should be carefully considered, as there is a large range of potential wind power across the roof. The influence that the surrounding urban environment has on the studied building is also worth noting, as it has an impact on roof-level flow characteristics. It should be noted that the wind conditions do improve as the height above the roof level increases; however, due to a lack of a sizable lot, the turbines would most likely be mounted on the building. Because the wind turbines would essentially be cantilevered from the building's structure, the retrofitted building's ability to withstand additional loading would need to be considered. It should be noted that a very small number of usable wind instances occur throughout the year result in stable flow at the roof-level. Additionally, because these flow characteristics are not consistent across the entire roof, the likeliness of low economic benefit should be strongly considered. This illustrates the importance of considering the effects of the surrounding urban morphology when formulating an initial design concept for the implementation of BIWT.

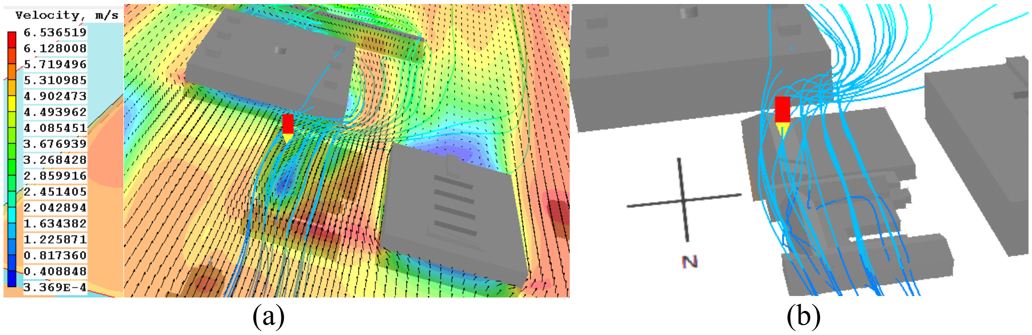



**Figure 8.** *Velocity vectors and streamlines showing the influence of (a) the building's site and (b) the building's geometry on roof-level wind flow from the north.*

## DISCUSSION

After completing this study, it is desired that this workflow be investigated within the context of Integrated Project Delivery (IPD). This process would be especially well-suited for the entity relationships within this project delivery method. Because the delivery team is assembled from the inception of the project, both engineers and architects would have the opportunity to begin their dialogue before building geometries take shape. This delivery method creates a systems-style approach to design, as all parties have an invested interest in the whole design working as effectively as possible, rather than having each party solely invested in their own particular component. The workflow developed within this study moves towards a systems-style approach to the design of the overall geometry of the building, additionally integrating the functionality of the turbine design into the structure's aesthetic. This workflow considers each part of the design interrelated, all contributing towards the overall success of the design. The workflow discussed in this paper essentially aims to maximize the benefit received from a balanced interaction between building-integrated wind turbines and the aesthetic of the building's design.

This style of project delivery, coupled with the workflow discussed in this paper, would enable a systems-style design approach that mimics the concept development processes prevalent in the automotive and aerospace industries. Current building design processes typically lack the systemic approach that makes progress and innovation so rapid in the aforementioned industries. The aerospace and automobile industries have employees across the divisions of a company working collaboratively so that everything from the conceptual design to the final product reflects input from all facets of the design team; this corresponds to a progressive, industry-wide decrease in Energy Use Intensity (EUI) over time. The building industry rarely operates in this fashion; one can coincidentally note that the building industry's EUI has not changed much in the past several years. The building industry is fragmented in that stages of the design process compete against one another, trying to ensure their own companies' maximum profit and minimum risk. This fragmented relationship throughout the design process creates inherent inadequacies in the flow of the information necessary to make informed, systemically considerate design decisions. This study illustrates an example of the potential of architectural design synergy. In a project type as complex as one which deals with wind harvesting, in which the success of a design is depended on factors as complex as urban microclimates, a scientifically-informed design process is important in contributing towards a product which is multi-dimensionally successful. The buildings in which we reside are complex systems, and each facet of the design is interrelated. The workflow proposed in this study attempts to recognize this and, in turn, allows both architects and engineers to work systemically throughout the design process.

## CONCLUSION

This study shows that many factors affect the success or failure of BIWT systems. The microclimate created by the urban morphology surrounding a site, as influenced by prevailing wind conditions, plays a huge role in whether or not a site is even feasible to propose building-integrated wind turbines. Additionally, the geometries of buildings themselves play a huge role in shaping the wind environment around a site. This study illustrates these points by providing analyses of several proposed designs, showing the importance of a building's geometry, with regards to the microclimate surrounding the envelope. The results of the study illustrate that a symbiotic relationship between architect and building scientist during the conceptual design phase of a project offers valuable insight early on in the programming and aesthetic design phases. This symbiotic relationship can contribute towards reducing some problems associated with serially-fragmenting the BIWT design process. This symbiosis can be used in a workflow, during which, each step of the process informs subsequent design decisions. Through this iterative, informed design process, a building's design will converge on a solution that optimizes both programmatic functionality and wind turbine performance.

## ACKNOWLEDGEMENTS

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# URBAN ELECTRICITY SYSTEMS: A UK case study

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The electricity sector worldwide is facing considerable pressure arising out of climate change issues, depletion of fossil fuels and geo-political issues around the location of remaining fossil fuel reserves. Electricity systems are also facing technical issues of bi-directional power flows, increasing long-distance power flows and a growing contribution from fluctuating generation sources. There is a concern that these systems are vulnerable. Investigation of vulnerability has focussed on shocks to the system associated with weather risks, equipment failure, supply (fuel) failure and price shocks, and analysis has been primarily based on financial measures such as the value of lost load.

As the UK electricity system makes the transition to a low carbon future, it is unclear what this new future will look like. Transition pathways research using a multi-level perspective has identified a general picture of the drivers in future systems architecture. In such futures, vulnerability becomes multi-dimensional, and security becomes a more complex issue than that of supply of fossil fuels. These issues are not specific to the UK. Electricity systems across the globe face the same issues of multi-dimensional vulnerability and complexity of security.

Research into the transition to a low carbon electricity system has, to date, been primarily focussed on the national scale in the UK. The aim of this work is a critical analysis into the use of the resilience concept for electricity systems, applied in particular to the distribution network in a case study urban area in the north east of England. The case study shall examine the low carbon scenarios for the UK, what this means in particular for domestic buildings for the case study area, and the nature of the stress on the electricity distribution system which may result from the expected growth in electrical load.

Key words: Electricity distribution, low carbon transitions.

## 1. INTRODUCTION

The electricity sector worldwide is facing considerable pressure arising out of rising global demand for energy services (Barrett *et al.*, date unknown; Ipakchi and Albuyeh, 2009), geo-political issues around the location of remaining fossil fuel reserves (Vivoda, 2012; Valentine, 2011; Coaffee, 2008; Nuttal and Manz, 2008), in addition to climate change issues (Eyre and Baruah, 2011; Grubb *et al.*, 2006).

The International Energy Agency (IEA) predicts a doubling in world energy demand from 2009 to 2035 (IEA, 2011). The most significant percentage growth in demand for energy occurs in the Middle East (growth of 1100%), China (growth of 432%), Asia (growth of 327%) and Africa (growth of 223%). Energy reserves are currently concentrated in relatively few nations around the world. In 2010, the top 5 oil exporting countries were responsible for 47% of global oil exports, 4 of which are members of the Organization of the Petroleum Exporting Countries (OPEC) (OPEC 2011). Middle East and North Africa (MENA) countries are home to 60% of world oil reserves and 49% of world gas reserves. Widespread political and social instability in this region, particularly the 2010 and 2011 "Arab Spring", led to oil price increases during that period (MENA-OECD Investment Programme, 2011).

With respect to climate change, the only legally binding international agreement to tackle greenhouse gas emissions is the Kyoto Protocol, developed in 1997 and ratified in 2005. Whilst international agreements on carbon emissions reductions have faltered at recent Conference of the Parties (COP) meetings, in 2009 the European Commission created legally binding targets for 20% reduction in greenhouse gas emissions and 20% contribution of renewable energy sources to overall energy consumption by 2020. The UK Government has a legally binding target to reduce greenhouse gas (GHG) emissions by 80% by 2050, compared to 1990 levels (Climate Change Act 2008). Associated with this target is a plethora of Government reports and legislation produced by the Department of Energy and Climate Change (DECC) which consider how this challenging target can be achieved (for example: DECC, 2009a; DECC, 2009b). The 2050 pathways report (DECC, 2010) demonstrated that scenarios achieving the 80% target involved significant electrification of the heat, transport and industry sectors in parallel with considerable decarbonisation of the electricity sector. Therefore, regardless of relatively slow growth predicted in the UK population, the growth in demand for electricity is predicted to be significant over the next 40 years.

## 2. ELECTRICITY SYSTEM RESILIENCE

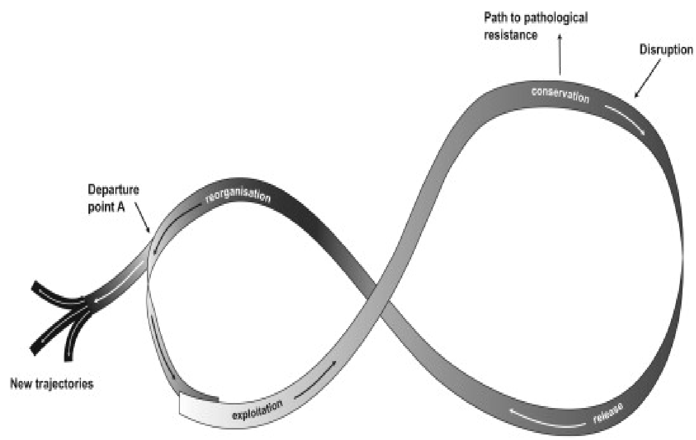
Historically, the security of supply discussion has been around supply side (e.g. Cohen *et al*., 2011; Jamasb and Pollitt, 2008) and technology performance (Chiaradonna *et al*., 2011; Grave *et al*., 2012). However, several research groups are investigating a wider concept of security (for example, Stirling (2009), Jansen and Seebregts (2010), O'Brien and Hope (2010), Goldthau and Sovacool (2012)). Included in these wider concepts is consideration of terms such as robustness, diversity, stability, durability, adaptability, sustainability, vulnerability, redundancy and resilience.

The UK government has focussed on security of supply with respect to reduced reliance on imports and robust supply chains and partnerships. For electricity in particular, the engineering focus has been on a robust system able to operate under loss of components, the "N-k" approach. The cost of this approach is complex to assess since it depends upon the system component under consideration (cable/wire, transformer, power station). For example, considering the UK electricity generation capacity margin of 14% in 2012/13 (OFGEM, 2012), and assuming the spare capacity of 7,948MW is combined cycle gas turbine technology with an average capital cost of £691.3/kW (PB, 2011), then the estimated capital cost associated with the 2012/13 UK electricity generation capacity margin is £5,494m.

With changes to the electricity infrastructure and reduced national self-sufficiency in oil and gas, it is no longer technical risk of outage, but geo-political uncertainties, price shocks and homeland security that have recently entered the vocabulary when discussing the UK electricity sector (Coaffee, 2008). It is also timely to consider indicators which go beyond the financial, such as value of lost load (Chaudry *et al*., 2009). Given the historical focus on security as an issue of supply of primary fuel, alongside more recent developments in the way we view issues of terrorism, interconnected infrastructure and smart grids, "security" as a term no longer seems appropriate. **Resilience** is proposed as an alternative appropriate term.

Resilience has been used in ecology to define the magnitude of disturbance which an ecological system can absorb before the system structure changes, described in work by Holling in 1973. Holling (an ecologist) described ecological resilience as the magnitude of the disturbance which can be absorbed before the system structure changes and a new equilibrium is reached (Davoudi, 2012). So the concept is not a return to the status quo, but the ability to adapt, change and transform. Holling's work has been expanded upon, for example Walker *et al.* (2004) define resilience as the ability to reorganise during change, to enable continued functionality.

Figure 1. Holling's adaptive cycle (reproduced with permission (O'Brien and Hope (2010)).




Within resilience thinking, the concept of change and evolution of systems is represented by the "adaptive cycle". The cycle comprises four stages.

1. There is a period of growth, with an abundance of resources, and an accumulation of structure.
2. There is a period of conservation, with a slowing of net growth, greater system interconnection and less flexibility.
3. There is a stage of release of bound-up resources where disturbance leads to accumulated structure collapse.
4. Finally there is a reorganisation stage where novel practice or technology can take hold (Walker *et al*., 2006).

Stages of the cycle are not necessarily sequential and one system may have elements with nested adaptive cycles operating at different scales and timeframes (Figure 1). Resilience as a term therefore enables a discussion of the electricity system's ability to adapt, change and transform rather than it's ability to return to "normal" within some prescribed range of operating conditions. Resilience as a concept can be applied to much more than the supply side and hardware. Instead, it enables a holistic approach to the system which is the electricity sector, and about the components which make up that sector. It brings in to the discussion a richness which addresses the social and the technical. Resilience provides a new definition of a healthy system.

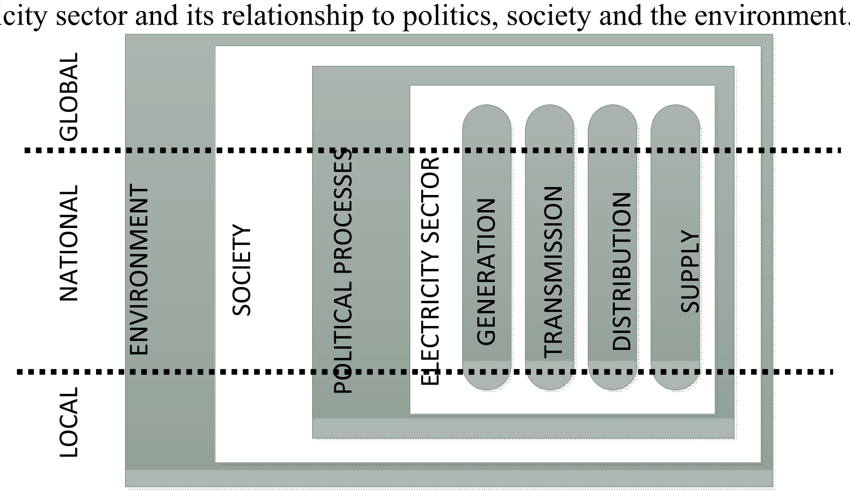
Within the adaptive cycle concept, where do the disturbances originate which lead to change? Multi-level perspectives in transitions theory are complementary to resilience theory in this regard. A multi-level perspective considers niche technologies at the micro scale putting pressure on the incumbent system at the meso level, and macro level pressures from the overall socio-technical landscape (Geels, 2002). This concept of a multi-level perspective enables an electricity sector resilience dialogue to incorporate global and local issues.

***In considering resilience and transitions theories, I propose a nested resilience model comprising environment, society, political processes and electricity infrastructure, incorporating global, national and local issues***.

This is shown in Figure 2. Note that in the UK, generation (ownership and operation of power plant), transmission (long distance transportation, at 400kV, 275kV and in Scotland 132kV, of electricity from large generation plant to distribution networks), distribution (short distance transportation, at 132kV and below, of electricity to end users) and supply (metering and billing of electricity end users) have been separated and privatised, and so each subsection of the electricity sector is shown separately in Figure 2. Different sub sectors may be appropriate in different contexts.

Qualitative and quantitative measures within each element of the resilience model can then be chosen, appropriate to the context under consideration. For example, in considering indicators of resilience for the UK electricity system an appropriate national scale societal indicator may be the number of households in fuel poverty. For the Sudan, it may be the number of households without a supply of electricity. The collection of qualitative and quantitative indicators can then be presented as a score card. Amalgamation of indicators to provide one measure of resilience relies heavily on quantitative measures and subjective weighting of components, and so is not recommended.

Figure 2. Representation of three scales, applied to a nested system to represent the electricity sector and its relationship to politics, society and the environment.



## 3. THE UK IN 2050 – A LOCAL PERSPECTIVE

In investigating the impact of 2050 scenarios (DECC, 2010) on the local distribution grid, the public domain EXCEL 2050 pathways calculator was used (DECC, 2012) along side details of the seven UK Government pathways to find the mean electricity consumption for households, based on heating, cooling, lighting, appliance and personal electric car loads (Table 1).

Table 1. Electricity consumption scenarios, 2050 pathways

| **Electricity consumption, 2050, TWh** | **Reference case** | **Alpha case: x sector** | **Beta case: low carbon capture and storage** | **Gamma case: low nuclear** | **Delta case: low renewables** | **Epsilon case: low bioenergy** | **Zeta case: low behaviour change** |
|---|---|---|---|---|---|---|---|
| H2 generation | | 51 | 51 | 51 | 51 | 133 | 141 |
| Overgeneration/exports | | 398 | 403 | 348 | 371 | 209 | 394 |
| Losses | 41 | 40 | 38 | 37 | 36 | 47 | 57 |
| Domestic heating & cooling | 61 | 114 | 114 | 120 | 88 | 134 | 211 |
| Commercial heating & cooling | 31 | 41 | 41 | 41 | 41 | 54 | 69 |
| Domestic lighting & appliances | 103 | 93 | 63 | 63 | 63 | 93 | 111 |
| Commercial lighting & appliances | 92 | 90 | 90 | 73 | 90 | 90 | 101 |
| Industry | 228 | 114 | 114 | 114 | 114 | 114 | 114 |
| Agriculture | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| Road transport | 14 | 25 | 25 | 25 | 25 | 0 | 0 |
| Rail transport | 14 | 25 | 25 | 25 | 25 | 1 | 0 |
| **TOTAL** | **588** | **995** | **968** | **901** | **908** | **879** | **1202** |
| Domestic elec. consumption total (TWh) | 164 | 207 | 177 | 183 | 151 | 227 | 322 |
| Total number of households (million) | 40.2 | 40.2 | 40.2 | 40.2 | 40.2 | 40.2 | 40.2 |
| Mean elec. consumption/household (kWh) | 4,080 | 5,149 | 4,403 | 4,552 | 3,756 | 5,647 | 8,010 |
| 2050 road transport: share which is personal car | 0.82 | 0.80 | 0.80 | 0.80 | 0.80 | 0.80 | 0.82 |
| Mean elec. consumption/household for road transport (kWh) | 286 | 498 | 498 | 498 | 498 | 0 | 0 |
| **Total mean elec. consumption/household (kWh)** | **4,365** | **5,647** | **4,900** | **5,050** | **4,254** | **5,647** | **8,010** |

Focussing on electricity consumption only, the results of the EXCEL 2050 pathway scenarios were then used in a simple electricity distribution grid model developed by colleagues at Northumbria University. The network model is based on a section of electricity distribution grid in an urban town in the north east of England, comprising a 400V 3-phase distribution system supplying 59 domestic properties (17 at node 2, 13 at node 3, 11 at node 4, 12 at node 5 and 6 at node 6). Annual consumption from the pathway scenarios was scaled to a 24 hour summer and winter demand profile for domestic load only. The simple grid model identified whether there were issues of node voltages exceeding guidelines, voltage drop exceeding guidelines, line current exceeding cable thermal rating, and transformer overload.

Line current exceeded cable thermal ratings for winter load conditions at node 2 for the reference, alpha, beta, gamma and epsilon pathways. Line current exceeded cable thermal ratings for winter load conditions at node 2, 3 and 4 for the zeta pathway. Line current exceeded cable thermal ratings for summer load conditions at node 2 for the gamma pathway. Only the delta pathway resulted in no current overload, in summer and winter. Node voltage exceeded the guideline of +10% in summer at all nodes for the alpha, beta, gamma and zeta pathways. Node voltage exceeded the guideline of +10% in winter at all nodes for the gamma pathway. Only the delta, reference and epsilon pathways resulted in node voltages within limits, in summer and winter. No pathways resulted in transformer thermal overload. However, the alpha, beta, gamma and zeta pathways resulted in reverse power flow through the transformer during periods of significant local generation. Whether this is possible will depend on the transformer installed. The highest reverse power flow was for the gamma pathway, of 0.923pu for summer.

An example of the results available from the grid model is shown in Figures 3, 4 and 5, for the gamma pathway scenario, for summer load conditions. Results show that, whilst on the national scale these scenarios meet the requirement for 80% greenhouse gas reduction and demand/supply balancing, on a local level the amount of load and generation predicted will cause problems for the existing distribution network, with regards reverse power flow through transformers, line current overload and voltage overload at times of peak local generation.

Only the delta pathway led to the existing distribution network operating within regulatory limits; this pathway requires significant electrification of thermal heat loads and major efforts to reduce demand.

Figure 3. Line section current, summer load conditions, gamma pathway.

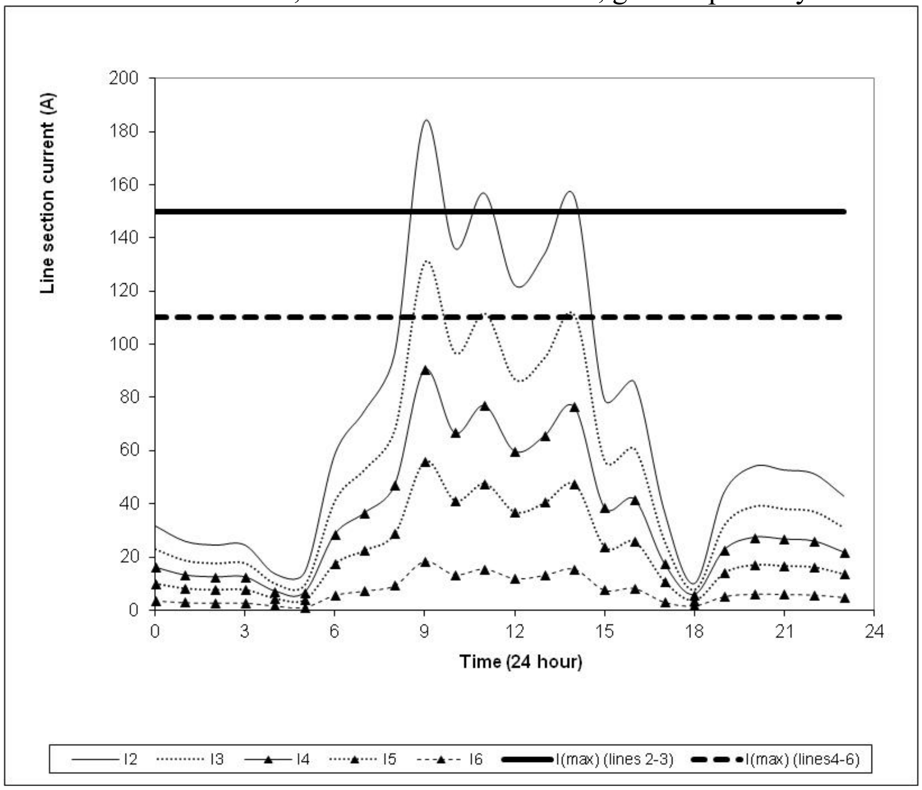



Figure 4. Voltage at nodes, summer load conditions, gamma pathway.

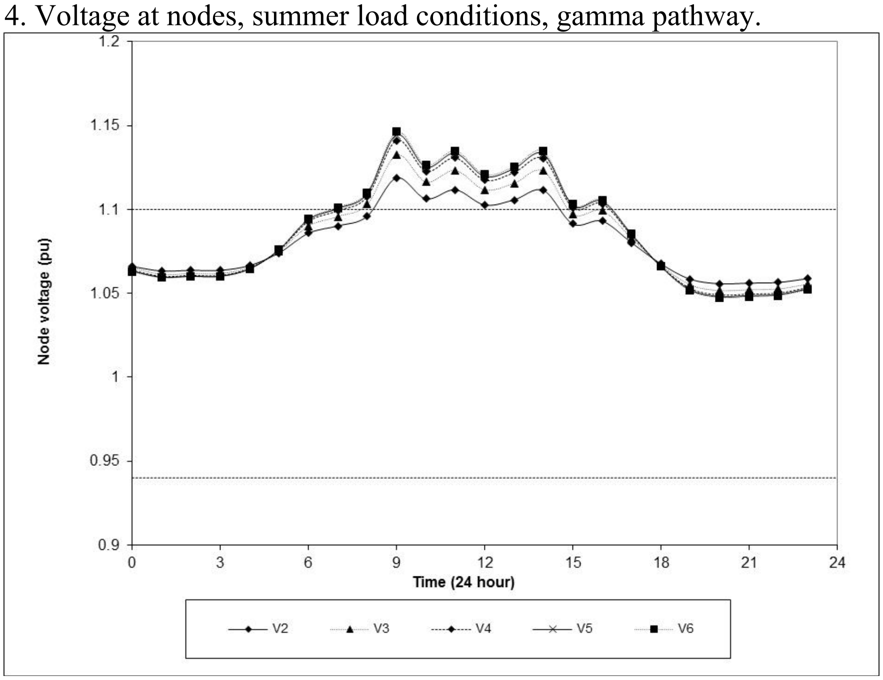
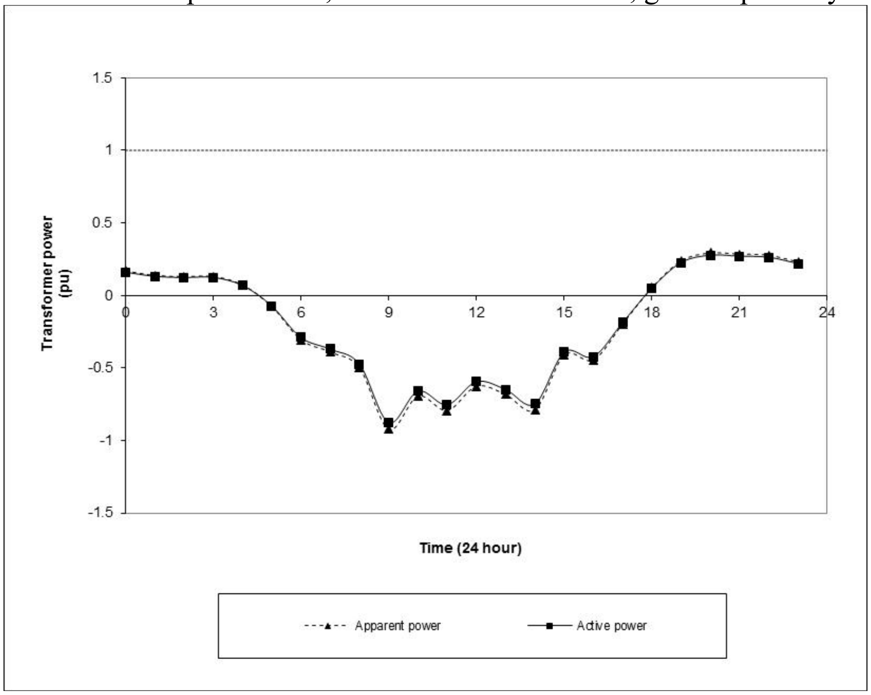


Figure 5. Transformer power flow, summer load conditions, gamma pathway.




Given the target to transition to a low carbon pathway, and the evidence shown that the existing distribution system is not capable of accommodating power flows in future low carbon scenarios, there is a window of opportunity during which resilience of the distribution network can be considered. The framework contained in Figure 2 recommends consideration of local, national and global resilience issues for the environment, society and the electricity sector. A more resilience distribution system may be possible if considering smart meters, load shifting and use of storage, for example, rather than proceeding down an N-k network reinforcement pathway.

## CONCLUSIONS

With climate change policy at the global level progressing extremely slowly and no replacement for binding Kyoto targets yet agreed, EU policy and UK policy has developed such that the UK has a binding target to reduce GHG emissions by 80%. To achieve this there are associated policy targets for decarbonisation of the electricity sector and a target to increase electricity generation from renewable energy sources to 30% by 2020. The importance of national infrastructure in delivering these targets has been recognised in the UK, contributing to the drive to create the National Infrastructure Plan 2010 and the creation of a unit within HM Treasury, Infrastructure UK.

Historical energy security concerns have grown around security of supply of primary fuels. Resilience as a concept enables a discussion of the electricity system's ability to adapt, change and transform rather than it's ability to return to "normal" within some prescribed range of operating conditions. A nested resilience model is proposed, comprising environment, society, political processes and electricity infrastructure, incorporating global, national and local issues.

UK 2050 pathways have been analysed elsewhere with respect to the national level. Considering the local level as incorporated in the nested resilience model, and using a simple distribution network model to determine the impact of 2050 pathways, it was found that only one of the six pathways which meet the 80% greenhouse gas reduction target (reference case is not an 80% reduction case) would require no investment or adaptation to the distribution network. It is recommended that transition to a low carbon electricity sector for the UK includes consideration of resilience of the local distribution network, taking a more proactive and flexible approach than simply network reinforcement.

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# Fire Safety Design and Construction Considerations for Sustainable Residential Structures

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## ABSTRACT

Within the past five years, new codes, policies and recommendations for construction and landscaping have been adopted to improve the sustainability of buildings and their operations. Residential buildings are now being designed and constructed with the goal of achieving sustainability – minimal impact on the environmental, very low to zero energy usage, use of sustainable materials, etc. Many building codes and other groups are promulgating "green" building codes. These changes to the design and construction standards for buildings offer the potential to increase building performance and decrease impact on the environment, but may also include, fire and safety challenges that have unintended consequences including increased property damage compromised related to life safety. Understanding and applying both wildfire safety and sustainable or "Green" principles can be complex and often conflicting. Impacted stakeholders include residents, business, land managers, landscape architects, landscape designers, foresters, fire authorities, building industry, planners and policy-makers. This paper presents and summarizes the information collected to support the future development of a systematic method for evaluating building designs that integrates the consideration of fire hazards as well as other hazard risk factors. This includes a review of current building and development codes, and design guides, an analysis of environmental factors affecting the potential of fire for residential structures, and conclusions regarding sustainable design and construction fire strategies.

**Key Words:** Sustainable Design and Construction, Residential Structures Building, Fire Safety.

## Introduction and Background

The United States annually experiences fatalities, injuries, structural losses, and environmental pollution as a result of fires. The National Fire Protection Association (NFPA) annually reports all fire types, including vehicles, industrial structures, high-rise buildings, outdoor, brush fires, etc. in the U.S. in the their annual fire loss report. For example, in 2004 the NFPA's annual study reported no significant reduction in fire losses and increases in some categories beginning in 2003. In 2003, fire related injuries approximately totaled 18,000; most of the injuries occurring in residential structures. Most structure losses occur in the first few hours of a major interface fire incident (MesKimen 2011). There are several factors that contribute to this loss: insufficient vegetation management; inadequate building standards; and insufficient firefighting forces (Bailey 2007).

**Review of current building codes, development codes, and design guides**

As building codes and other groups are promulgating the design and construction sustainable “green” structures, a literature review included building codes, development requirements, and design guides commonly used.

Examples of model codes found included two National Fire Protection Association (NFPA) Standards: NFPA 1144, Standard for Reducing Structure Ignition Hazards from Wildland Fire 2008 Edition (NFPA 1144); and NFPA 1141, Standard for Fire Protection Infrastructure for Land Development in Suburban and Rural Areas 2008 Edition (NFPA 1141).

NFPA 1144 provides minimum standards for design, construction, and landscaping for structures in the wildland urban interface (WUI), and reducing the probability of ignition. The standard applies to all existing structures and improvements within the WUI. The optimal goal of NFPA 1144 is to prevent ignition of residential structures, and for those structures to survive a wildfire without the intervention of firefighting force (National Fire Protection Association 2008-B).

NFPA 1141 provides guidance for fire protection and emergency services in suburban and rural areas. NFPA 1141 applies to land development or changes in land use (subdivisions) within suburban and rural areas (National Fire Protection Association 2008-A). Each of these codes references the other for additional information, and they are intended as complimentary documents. The two separate documents are established to allow jurisdictional flexibility in applying the WUI standards (National Fire Protection Association 2008-A).

The International Code Council (ICC) publishes the three codes not produced by the NFPA. The ICC designs all of the International Codes (I-Codes) to be promulgated by adoption into ordinance. For example, the California Building Code (CBC) is based upon the ICC-published International Building Code. The California State Fire Code (CFC) also originates within the ICC as the International Fire Code. Both the International Building and Fire Codes are adopted with amendments by the California Legislature and become law (Office of the State Fire Marshall 2009). Additionally, the ICC publishes the International Wildland-Urban Interface Code (IWUIC 2009) as a stand-alone adoptable model code for WUI areas (International Code Council 2009). CBC, Chapter 7A and CFC, Chapter 49 are enforceable regulations in State Responsibility Area (SRA) Lands and in local jurisdictions where adopted (Office of the State Fire Marshall 2009).

CBC Chapter 7A (International Code Council 2009 February) includes sections addressing fire in the Wildland Urban Interface (WUI), “Materials and Construction

Methods for Exterior Wildfire Exposure." It offers performance-based solutions as an alternative to prescriptive code requirements. The emphasis of CBC Chapter 7A is on preventing structure ignition from flame and burning ember intrusion in areas prone to wildfires. It specifies, in conjunction with local jurisdictions, requirements for defensible space, access, roadside clearance, ignition-resistant materials and methods of construction. The code requirements can be met in either a performance or prescriptive manner; however, as part of the California Building Code, CBC Chapter 7A only limited information is offered on the design and relatively safe integration of structures into a potential incendiary environment. It is therefore the responsibility of local governments to establish fire safety requirements and procedures specifically for their communities (MesKimen 2011).

**Environmental factors affecting the fire potential around residential structural**
Three interacting classes of variables influence the potential threat that fire has on structures: surrounding sources of fuels, weather conditions, and site topography (National Wildfire Coordinating Group 2001). The fuels component varies considerably in both space and time. Weather is the most variable component changing in terms of time and space. Topography does not vary temporally, but can vary greatly spatially (Pyne et al. 1996).

*Surrounding Sources of Fuels*
A wildland fire does not spread to homes unless the homes meet the fuel and heat requirements sufficient for ignition and continued combustion. Ignition and fire spread to exposures are a proximate process primarily influenced by adjacent available fuels: "Fire spreads as a continually propagating process, not as a moving mass. Unlike a flash flood or an avalanche where a mass engulfs objects in its path, fire spreads because the locations along the path meet the requirements for combustion (Cohen 2003)."

Vegetation fuels respond to varying conditions of sunlight, temperature, soil composition and moisture. The layout of the landscape influences these vegetation variables and significantly contributes to the type and amount of fuel available (Pittenger 2002). Furthermore, fuel moisture and consequently the combustibility of natural and landscaped vegetation vary with respect to elevation (National Wildfire Coordinating Group 2001) (National Wildfire Coordinating Group 1994).

*Atmospheric and Weather Conditions*
Atmospheric and weather components, also known as air mass, include factors of temperature, relative humidity, air movement, cloud cover, precipitation, and atmospheric stability. These values can vary significantly depending on elevation and geographic locations. Air mass affects fire by regulating the moisture content of fuel, and more directly the rate of combustion (National Wildfire Coordinating Group 2001). The predominant factor affecting direction and rate of wildfire spread is given a "driven" designation (i.e. wind-driven fire). Weather is the primary driving

force behind changes in fire behavior, with wind direction and velocity changes producing significant rapid burning alterations (Tele 2005).

Atmospheric temperature also affects surrounding sources of fuel temperature and burn rate. The ease of ignition, the amount of heating required to raise fuel to ignition temperature depends on the initial fuel temperature (National Wildfire Coordinating Group 2001). For example, for every 18°F increase in temperature the speed of a chemical reaction doubles (Tele 2005). The most important effect of temperature is its effect on relative humidity and therefore affects the dead fuel moisture content (National Wildfire Coordinating Group 2001). Wind is the most influential factor of the weather class when it some to the burn rate and direction of spread (Tele 2005).

Windspeed has a significant effect on fire spread, by providing increased oxygen to the fuel and materially determines the rate of spread and burn direction. A five mile-per-hour wind will impact rate of spread in the same way as a 50% slope (Tele 2005). Increased wind velocity moves flames increasingly horizontal from vertical, and can cause direct flame contact with fuel ahead of the fire. Wind affects fuels by reheating and drying them by increasing the rate of transfer of radiant and convective heat (National Wildfire Coordinating Group 2001). Convective heat plays the greater role in the spread of wildland fire as superheated smoke and gasses preheat fuels, cause spot fires, and move fire into the crowns of trees (Tele 2005). Wind propels embers carrying them further as wind velocity increases. Spotting occurs possibly ten minutes before the arrival of a flame front during a wildfire (Tele 2005).

Not only can embers destroy structures before the arrival of a flame front, but they may also ignite structures afterwards. Research has shown that the majority of houses destroyed in Australian wildfires actually survive the passage of the fire front only to burn down in the following ignitions caused by windborne burning debris. The prolonged ember attack mechanism stemming from spotting is the main cause of structural losses in the UWI (Stephens and Collins 2007).

*Site Topography*
Site topography variations include the land shape, elevation, slope direction, sunlight exposure, and slope steepness. Site topography affects airflow by increasing or decreasing velocity and redirecting it (Fovell 2008). The shape of the land influences how much sunlight or shade an area receives, which affects temperature, fuels, and airflow (Tele 2005).

The positioning of a structure within the topography is a very critical factor in fire exposure. The slope of terrain affects fire behavior and has several interactions on fuels and burning rate. Steep slopes and deep drainages promote significant preheating of fuels, producing rapid upslope and up valley fire spread. Extreme fire behavior is associated with steep sloped conditions (Los Angeles County 2010). Besides uphill fires preheating fuels, the fuels on steep slopes have lower fuel moisture, because elevation impacts how much wind and moisture an area receives.

The closer the slope is to perpendicular, the greater the amount of solar radiation. The higher the level of radiation, the higher the temperature and the lower the fuel moisture will become (Tele 2005).

Slope steepness is important in that it contributes to how quickly the fire will reach the crest of the landform. Most important topographic effect is that fire spreads much faster uphill than downhill, without significant wind influence (Los Angeles County Fire Department 2010). Other fire spread variables remaining constant, a fire burning on level ground will spread twice as fast when it reaches 30% slopes, and the rate of spread will double a second time when the slopes reaches 55% (Los Angeles County Fire Department 2010). A significant fire spread effect is portrayed when comparing uphill versus downhill rates of spread (MesKimen 2011).

Fire can travel sixteen (16) times faster uphill than it can travel downhill (Payne et al. 1996). This relationship is accomplished in part by topographical wind. Topographical airflow is created by convective currents. Assuming ambient wind is constant, topographical airflow increases the fire rate of spread uphill, and decreases the rate of spread downhill in a diverse spatial mode in the leeward direction (Rehm and Mell 2009). Faster uphill fire travel is nearly a universal truth, with one known noteworthy exception. United States Forest Service personnel have documented the fastest downhill fire spread rates occurring in the County of Santa Barbara, CA coastal regions (MesKimen 2011).

In addition, increased rates of spread, flame length, and heat energy release rates are correspondingly greater as the slope increases (Radtke 2004). Topographical obstacles strongly affect atmospheric airflow. Wind traveling over hills generally creates eddies (turbulence) over the crest and descending partially down the leeward side (National Wildfire Coordinating Group 1994). Slopes can increase fire spread by enhancing the transport of oxygen from the atmosphere to the fuel by reducing the depth of the laminar airflow boundary layer around the fuels (Kochanski et al. 2009).

**Sustainable design and construction fire prevention strategies**

These terrain and construction factors combined to significantly increase the fire resiliency of the residence. In a research project recently completed as California Polytechnic State University, San Luis Obispo, the following strategies were found to contribute to increasing safety - these include selection of non-combustible materials for the building envelope, limiting ember intrusion, creating structure safety zones and defensible spaces, lowering wind turbulence of building envelopes, constructing structural fire shields, providing slope setbacks for structures, providing on-site sources of fire protection water (MesKimen 2011).

*Selection of Non-Combustible materials for Building Envelopes*

Increasing the fire resistivity of the building envelope includes selecting non-combustible materials for roof assemblies, eaves and gutters, exterior wall assemblies, exterior doors and windows, decks, etc. For example, the single pane windows allow radiant heat inside the structure. In addition, single pane windows breakout easily during fire situations (National Fire Protection Association 2008-A).

A recently published report by the Fire Protection Research Foundation (FPRF) cited the following as exterior components and materials commonly used in the construction sustainable structures as potentially increasing the risk of fire (Meacham et al (2012).

- Structural integrated panel (SIP)
- Exterior insulation & finish (EFIS)
- Rigid foam insulation
- Spray-applied foam insulation
- Foil insulation systems
- High-performance glazing
- Low-emissivity & reflective coating
- Double-skin façade / cavity wall
- Bamboo, other cellulosic
- Bio-polymers, FRPs
- Vegetative roof systems
  - Insulating material
  - Thickness
  - Type of vegetation
- PVC rainwater catchment
- Exterior cable / cable trays
- Extended solar roof panels
- Awnings / exterior solar shades
- Exterior vegetative covering

Material property standards include: ASTM E 1623, NFPA 268, and UL 197. This fire-test-response standard assesses the response of materials, products, and assemblies to controlled levels of radiant heat exposure with or without an external ignitor. The fire-test-response characteristics determined by this test method include the ignitability, heat release rates, mass loss rates, visible smoke development, and gas release of materials, products, and assemblies under well ventilated conditions.

This test method is also suitable for determining many of the parameters or values needed as input for computer fire models. Examples of these values include effective heat of combustion, surface temperature, ignition temperature, and emissivity. This test method is also intended to provide information about other fire parameters such as thermal conductivity, specific heat, radiative and convective heat transfer coefficients, flame radiation factor, air entrainment rates, flame temperatures, minimum surface temperatures for upward and downward flame spread, heat of gasification, nondimensional heat of gasification (1)2 and the F flame spread parameter.

Ignition and combustibility standards include ASTM E-136 and ASTM D 1929. These fire-test-response standards cover the determination, under specified laboratory conditions, of combustion characteristics of building materials and the flash ignition temperature and spontaneous ignition temperature of plastics using a hot-air furnace. This standard is used to measure and describe the response of materials, products, or assemblies to heat and flame under controlled conditions.

*Limiting Ember Intrusion*

A primary cause of structural fires has been identified as the intrusion of embers into the structure (Institute for Business and Home Safety 2008). Ember intrusion can occur in concealed spaces, attics, roof underlayment, architectural features, and interior spaces. All of these areas require additional protection. Unprotected attic vents and open eaves can allow fire embers to intrude into the limited attic space (MesKimen 2011).

*Creating Structure Safety Zones and Defensible Spaces*
In major conflagrations, fire protection agencies often do not have enough personnel and equipment to defend and protect every home and therefore residents cannot completely depend on a fire agencies help. One of the principal responsibilities of firefighters is to stop the spread of fire from house to house. As an example, one engine company is needed for every two structures in a clustered development with less than 50 feet separation, and one engine company per structure that is surrounded by vegetation (National Wildfire Coordinating Group 1991).

Defensible space refers to a managed vegetation area adjacent to structures where wildfire protective practices have been implemented. The primary objectives of defensible space are protecting structures from an approaching wildfire, and where firefighting can take place in relative safety (State Board of Forestry and Fire Protection 2006; California Emergency Management Agency 2010). The emphasis of structure survival during fires is recognized as vegetation management by Bailey (2007, 5) who argues: "During major fire operations in the interface, most structure loss occurs in the first few hours of an incident. This includes eliminating highly flammable trees adjacent to structures and managing the height and density of low flammability of the vegetation to prevent fire from spreading to adjacent structures (MesKimen 2011). The prominence of WUI fires, and the preventative actions taken in response to this problem by private and government entities, has established these protective actions as nationally recognized "good practice".

*Lowering Wind Turbulence of Building Envelopes*
This concept involves limiting the turbulence caused by the shape of the building envelope. Contributing structural components include walls, roof, and other architectural features. Flat roof with parapet walls can have beneficial to increasing the fire resiliency of the structures. This is primarily due to the lack of attic spaces and attic vents which reduces the possibility of ember intrusion into the structure (MesKimen 2011). Parapet walls and flat roofs section also presented a low airflow impact shape, allowing the flames to traverse above the structure without any visible fire consequences

*Constructing Structural Fire Shields*
Structural fire shield protect structures by uplifting of the airflow and flames over the roof of a structure. Retaining walls have been used effectively to provide flame and fire ember protection. When retaining walls are constructed at the base of an inclined terrain, they are able to protect exterior wall openings from direct flame and ember

contact. Essentially, retaining wall adjacent to structures can perform two functions. First, separate the structure from the terrain to form a fire shielding protection, and second, present a lower vertical profile of the building envelope to the approaching fire (MesKimen 2011).

*Providing Slope Setbacks for Structures*
According to Brown, the third most significant structure-survivability predictor, following noncombustible roofs and defensible space is slope steepness (Brown 1994). In case studies of WUI fires performed by the National Fire Protection Association, structures located on slopes, exceeding 20%, experienced damage or destruction during interface wildfires (Brown 1994).

*Providing On-site sources of fire protection water*
On-site sources of water which can be used for the protection of a structure are helpful in mitigating losses due to fire This includes providing sufficient fire flow characteristics such as quantity, residual pressure, firefighting access to water supply and system reliability. In addition, this includes providing adequate emergency water supply independent of any existing municipal water system. An independent water supply includes fire authority-approved methods of delivery from stored water to water systems to backup power for fire pumps (MesKimen 2011).

## Conclusion and Recommendations for Future Research

In conducting the research, it was found that there are currently no fire incident reporting systems in the United States or other countries which specifically collect and track data on fire incidents in buildings labeled as “green buildings” or specific components of building that are considered “sustainable”. Therefore it recommended changes are made to reporting systems such as National Fire Incident Reporting System (NFIRS), it difficult to track this level of fire incident data.

Studies related to green building and fire issues produced by BRE, BRANZ, FMGlobal and the NASFM have been identified. Research on specific building elements with green attributes, but not necessarily labeled as green, such as lightweight engineered lumber (LEL), has been identified at UL and NRC Canada, further research is needed to develop a comprehensive list of green building site and design features / elements / attributes. In addition, a list of fire-related hazards and risk factors, associated with green building elements should be developed in order to proceed with research on identifying specific elements of sustainable structures that are more susceptible to fire incidents.

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# Sustainability through collaboration-based corporate social responsibility

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**Abstract**

Sustainable development requires the integration of social, environmental and economic considerations into the developmental processes that impact on the environment in order to achieve equity and balanced judgments for long term sustainability. This paper explores the concept of sustainability of engineering projects from the perspectives of corporate social responsibility within the framework of collaborative planning. Corporate social responsibility which is the commitment of businesses to the sustainable economic development of their host communities and of society at large aims essentially to achieve the goal of environmental sustainability. The principle collaborative planning explores consensus-building and mediation in resolving the construction projects interest group conflicts between the project proponents and other stakeholders, in resolving pre-project, project and post-project environmental and socio-economic concerns.

This paper argues that collaborative planning is a medium through which the declared fiduciary social contract (the social corporate responsibility) that exist between construction projects and indeed its business promoters and their host communities can be negotiated to ensure that as they achieves their goal of profit maximisation, the host community also benefits through investments in social capital and good environmental management to achieve sustainable building. The paper starts with explanations of the concept of corporate social responsibility and explores the conceptual imperatives of these for sustainable development through collaborative planning.

## Corporate Social Responsibility (CSR)

Corporate social responsibility is the commitment of businesses to the sustainable economic development of their host communities and of society at large, while also benefiting the lives of the workforce and their families (Dahlsrud, 2008; Welker, 2009; Ekwo, 2011). It is the concept whereby companies integrate social and environmental concerns in their business operations and in their interactions with stakeholders on a voluntary basis, to ensure a mutually beneficial relationship (Pava and Krausz, 1996; Hess *et al.*, 2002).

According to (Frynas, 2005; Ekwo, 2011), companies involved in engineering projects now attach more importance to their social, economic and environmental impacts on the host communities in order to secure the buy in of the stakeholders. The impacts range from marked changes in a community's means of subsistence and the transformation of community ways of life to the destruction of a community's environment and amenities have been repeatedly caused by construction companies (Jenkins and Yakovleva, 2006).

Analysis of the place of corporate social responsibility in the business and operational policy thrust of construction companies aim to synergise interest of all stakeholders, to promote a mutually beneficial overall relationship between host communities and construction companies in order to obviate the negative environmental externalities of their operations to achieve sustainable environmental (Rondinelli and Berry, 2000; Newell and Frynas, 2007).

### The integrative social contract approach to CSR

According to Moir (2001), the integrative approach looks at how business integrates social and environmental demands and concerns into its activities. It is argued from this position that business depends on society for its very existence, growth and continuity. Social demands are generally regarded as a way in which the society interacts with business in order to give it moral legitimacy and prestige (Knox and Maklan, 2004; Maignan and Ferrell, 2004). This approach presupposes that construction projects have to take into account, social and environmental considerations and integrate them in such a way that they operate in accordance with social values, leaving minimum impact on the environment. In this context, the content of CSR is seen as aiming to synergise the collaboration of the stakeholders in the host communities for greater sustainability of its activities.

The proponents of this approach contend that the business must respond to the social and environmental demands of their host communities and other non-shareholder stakeholders in order to achieve the greater social legitimacy and acceptance necessary for the stable environment required for business growth and development (Swanson, 1999). This approach is inclined to favour the integration of the relevant concerns of other stakeholders beyond the shareholders into the operational exigencies of the construction business. Integrative theorists place great importance on the way in which construction business may make a difference to the environment in which people live and work, by fostering and maintaining relationships with communities, being a good neighbour and contributing to sustainable development initiatives by collaborating with the people (Schwartz and Carroll, 2003).

Schwartz and Carroll (2003) analysed the relevant issues regarding the integration mechanisms a construction organisation must have in order to sensitise its corporate mission to the social and environmental challenges of its activities within the host community. They argue that social and environmental considerations should spread and be integrated across the organisation through a mechanism they termed "institutionalisation", meaning these concerns should be imbibed as part of the ethical principles of the construction business so that implementing them will be devoid of administrative bureaucracy, emphasizing a recognised process in addition to the appropriate principles laid down as part of the mission statement of the organisation.

The concept of social responsiveness of business within the community as a way of achieving corporate social responsibility has expanded in the past two decades because of the demand that businesses engaged in construction projects shift their corporate social responsibility strategy from reactionary to careful planning with inputs from the host community. This way, businesses have corporate social responsibility provided for in their long term organisational development planning (Knox and Maklan, 2004). This includes the integration mechanism canvassed by Schwartz and Carroll (2003) which also emphasises the process for making a reasoned response to the social issues generated by the activities of a business within its host community.

The incorporation of management issues in relation to corporate social responsibility has been suggested by Waddock and Graves (1997) as a way of influencing corporate organisations' strategies, and involves the process by which corporations can identify, evaluate and respond to social, political and environmental issues which could impact on them significantly if left to chance. In this regard, corporate social responsibility is an early warning system for potential environmental threats and opportunities for working with the community to achieve sustainable development. Furthermore, this approach to corporate social responsibility prompts more systematic and effective response to issues that perturb organisational interests by serving as an integrating and coordinating mechanism for engagement with the host community through the practice of collaborative planning.

## Stakeholder management

Stakeholder management is oriented towards those people in the communities affected by the corporate and operational practices of the construction business (Clarkson, 1995; Ekwo, 2011). Academic development of the debate around stakeholder management as an approach to corporate social responsibility is fairly recent, starting only towards the last quarter of the 20$^{th}$ century (Wood, 1991; Orlitzky *et al.*, 2003). Two basic principles underpin the stakeholder management approach (Wood and Jones, 1993; Friedman and Miles, 2006). The central goal of the first principle is the achievement of sustainable overall cooperation across the entire system of stakeholder groups in the business for sustainable development. The idea is to achieve a balance between the profit motives of the shareholder stakeholders (construction business owners) and the social contract expectations of the non-shareholder stakeholders (host community members). The second principle involves a vision of simultaneously dealing with issues affecting all stakeholders as they arise in equitable ways and ensuring that shareholder and non-shareholder interests are reflected in the corporate social responsibility initiatives of the business.

The stakeholder management approach rests in the integration of the interests of stakeholder groups into the mainstream decision making processes of the organisation. The utility of this approach lies in applying it to determine best practices in corporate stakeholder management. Scholars in the first decade of the 21$^{th}$ century, according to Hillman and Keim (2001), have looked at different aspects of the impacts of stakeholder management on the profitability of the business and returns on investment for shareholders. According to them, this has included research into various aspects of shareholder networks on the structural aspects of company policies concerning the extent of business involvement in corporate social activities within the community. Other proponents of the stakeholder management approach have also looked at the effects of balancing two competing demands: those of various stakeholder groups on the social contract between the business and the host community; and communities' reactions to changes in the attitudes of businesses to social investments in the society. It is submitted in this regard that giving host community members the status of stakeholders creates a foundation for building a symbiotic social relationship that will further the corporate social performance of the business in the host community through collaborative planning (Garriga and Melé, 2004).

### Ethical approach to corporate social responsibility

Another approach to corporate social responsibility according to Weaver *et al.* (1999) focuses on the ethical requirements that should form the basis of the interactions between the business and the host community. The ethical approach is based on the principle of the need to do the right thing in order to achieve a fair and just society. This approach to corporate social responsibility is normative and based on stakeholder management, which seeks to integrate the social demands of relevant stakeholders in the conceptualisation and management of social engagement with the host community (Garriga and Melé, 2004).

Following this approach, therefore, a socially responsible business, in fulfilment of its fiduciary duties to stakeholders, is required to simultaneously attend to the legitimate interests of all stakeholders. This it must do equitably, giving effect to the legitimate demands of the weak and vulnerable as well as the aspirations of the strong and mighty among the stakeholder pool (Freeman and Velamuri, 2008). In order to construe how corporations should be governed and how managers act when they have overarching responsibility for managing the fiduciary social contract with other stakeholders, a normative element of ethical principles is required (Freeman and Velamuri, 2008). As a result, different stakeholders have proposed differing elements of the normative principle, including the Rawlsian and the Kantian principles (Freeman and Velamuri, 2008). The Rawlsian principle is based on equity and fair-play on the part of the company in dispensing its corporate social responsibility patronage which can be achieved through collaborative planning to achieve sustainable development.

### Sustainable development

Many definitions of sustainable development have been proposed (Westing, 1996; Brandon and Lombardi, 2010a). However, a content analysis of the numerous definitions so far, according to Brandon and Lombardi, (2010b), suggest that sustainable development is a process of achieving human development in a manner that is inclusive, equitable, prudent and integrative. Therefore, sustainable development is an ideal towards which society's business and host communities should continually strive, through a detailed programme of collaborative planning to create values and outcomes that are consistent with the ideals of sustainability, including its "social, environmental and economic considerations" as these are part of sustainable development.

The approach has as its driving principle the objective of supporting companies to observe environmental, economic, social, and political justice in the communities where they do business (Clark *et al.*, 1998; Weissbrodt and Kruger, 2003). The universal rights principle is based on the Declaration of Human Rights and other international declarations on human rights, labour rights and environmental protection, all of which were adopted by the United Nations in 1984 (Weissbrodt and Kruger, 2003). Implementation of these conventions towards the goal of achieving corporate social responsibility by businesses in their host communities has been based on consensus rather than enforcement, and this has led to the proposition by many scholars that universal rights are mere declarations which need not be enforced on businesses, especially multinational ones.

Although the Brundtland report (World Commission on Environment and Development, 1987) was originally intended to highlight issues of the environment and sustainability (Blowfield, 2005; Pianta, 2005), its scope has since expanded to include considerations of social dimensions as being inseparable from business and development. Sustainable development requires the integration of social, environmental and economic considerations into business and other developmental processes that impact on the totality of the environment in order to achieve environmental justice, equity and balanced judgments for long term sustainability (United Nations, 2000). As a result, sustainable development gained universal acceptance as the preferred way companies should relate to their environment as they conduct their business in communities around the world.

## The collaborative planning debate

The collaborative planning principle explores consensus-building and mediation as a way of moving beyond interest group conflicts, in resolving pre- and post-project environmental and socio-economic concerns (Healey, 1997). The principle emphasises the potential for collaborative discussion of shared concerns about local environmental change, through which the affected community could learn about potential impacts and possible ways of evaluating and addressing identified project impacts, which could, in addition to its negative environmental externalities, have social and economic impacts on the people (Healey, 1997; Kovács and Paganelli, 2003).

In the management of large scale infrastructural systems, according to Kovács and Paganelli (2003), provision should be made for a planning and management framework that engenders the collaboration of stakeholders across the infrastructure network for complex, distributed, multi-site, multi-enterprise organisations - particularly where there are large-scale engineering projects, characterised by huge investments in both materials and human resources, which are likely to have environmental and socio-economic costs. They stated that a collaborative administrative vehicle will be required to provide an oversight function with respect to cumulative ecosystem impacts. Such an institutional framework would galvanise all the stakeholders, with a view to forging a common ground for collaboration for the monitoring of the environmental and socio-economic problems caused by a particular project.

Stakeholder collaboration can be enabled through the agency of geographic information systems. This will ensure that for all the various stakeholders concerned in the project, a consensus building avenue is built across the communities traversed by linear infrastructure (Barratt and Oliveira, 2001). Communities and institutions along the linear infrastructure corridor must act together to maximise resources - such as critical local knowledge in the communities; and technology -such as geographic information systems and finance - to achieve the sustainable management of building projects within their communities.

### Collaboration imperative of contracting with the people

In operational terms, collaborating with the people in the host communities of major infrastructures can tap into the existing social capital in order to encourage a focus on developmental interventions that use local organisations, create networks between organisations and use participatory practices for planning, implementing and monitoring activity and diffusing information (Cotton *et al.*, 1998; Coudouel *et al.*, 2002).

Collaborating with people has proved to be a veritable means of securing their involvement in the implementation and realisation of long term sustainability in Sri Lanka (Cotton *et al.*, 1998). The success factor in the Sri Lankan community contract initiative lies in the interest people acquired in the project by becoming a stakeholder. This generated a feeling of ownership of the projects by the community, and engendered in them a sense of responsibility for protecting them against vandalism, as this will affect community members who depend on the functioning of the project for their survival. This explains why some community groups who engage in the protection of common community property are able to resolve their collective grievances in a way that will not antagonise their common economic and social interests in public projects on their community land and other land, even when a stake in the project may not have immediate positive economic benefit for them (Goodhand *et al.*, 2000).

It can therefore be argued therefore that community stakeholders possess the capacities for a wholly endogenous solution to post-implementation infrastructure management challenges, to the extent that community stakeholders and governmental and other stakeholders can see the long term sustainability of the project as the collective aim of all.

## Conclusion

This paper has shown the tensions and strain between the actors in the social system that are common to the fiduciary relationship that exists between businesses such as oil companies, the state and the host communities in which these operate. This un-negotiated relationship has always resulted in the businesses and the state taking sides to the disadvantage of the weaker parties (the host communities) and, as a result, the communities are left in poverty with a decayed infrastructure, in contrast with what exists in the communities inhabited by the staff of the big organisations. These organisations are located and, in most cases, are destroying communities which were largely content with the hitherto serene natural environment.

The review indicates that the deliberate means through which corporate organisations and the state might honour their fiduciary duties to these communities are to be found in the equitable concept of corporate social responsibility (Aguilera *et al.*, 2004; Jenkins, 2005; Matten and Moon, 2008). This equitable concept provides a means of providing and preserving the basic structure of the system and adjusting to changing conditions within the framework that the basic structure provides (Jenkins, 2005). The social contract commitment of business to the community, if delivered properly, is a commitment towards the demands of the universal concept of sustainable development (Brundtland, 1987; World Commission on Environment and Development, 1987). Furthermore, the review shows that the objectives of corporate social responsibility, as a commitment towards the ideals of sustainable development, can be implemented through a framework based on the principles of collaborative planning practice, which provides for the democratisation of the processes involved in taking decisions about the environment with other stakeholders.

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# LOW CARBON CONSTRUCTION MATERIALS AND TECHNIQUES FOR SUSTAINABLE HOUSING DEVELOPMENT IN NIGERIA

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## Abstract

Housing is central to quality of life and consumes large amounts of resources in its construction, maintenance and use. It contributes significantly to sustainability because it consumes a substantial proportion of the global greenhouse gases. The building industry consumes a substantial percentage of the materials entering the global economy, and is responsible for the emission of almost half of the global greenhouse gases. Sustainability is achieved in housing through minimizing climate change, reducing pollution and improving air quality and health, and thus creating sustainable settlements. In Nigeria building earth is the indigenous material for construction and has been used for centuries. Extensive research has been carried out in the country, notably by the Nigerian Building and Road Research Institute which has resulted in the use of stabilized blocks for walling offering low-carbon solutions. This research focuses on the development of the blocks as innovative low carbon construction materials for housing construction in Nigeria. It discusses the potentials of the blocks in minimizing negative impact on the environment and thus enhancing sustainable housing.

**Keywords:** Carbon, Housing, Materials, Sustainable, Techniques**.**

## 1.0 INTRODUCTION

Sustainable architecture is a general term that describes environmentally low carbon materials and construction stating the usefulness and reasons for its proposed use for sustainable housing in Nigeria. It seeks to minimize the negative environmental impact of buildings by enhancing efficiency and moderation in the use of materials, energy, and development of space. Sustainable architecture describes an energy and ecologically conscious approach to the design of the built environment. The adoption of low carbon materials and construction techniques is a pragmatic approach to sustainable architecture. This is important in enhancing health, welfare and productivity of occupants of buildings, and it is cost effective particularly in housing construction.

Housing is one of humanity's important needs and it is an essential requirement for our existence. Adequacy in housing enhances the welfare and the productivity of people, and conversely its inadequacy threatens the very basis of human existence (Olotuah, 2012). The place of housing in human life is eminent necessitating its adequate provision in quantitative and qualitative terms (Adedeji, 2012). Housing, as a process, is the all-encompassing phenomenon of the creation of the living environment for human. It caters for human biological (clean air, water), psychological (satisfaction, contentment, prestige, privacy, choice, freedom, security) and social (interaction with others, human development and cultural activities) needs and is beneficial for human development (Olotuah, 2012).

A great quantum of Carbon dioxide ($CO_2$) is emitted to the atmosphere through the whole life-cycle of a building, hence it is vital to seek housing solutions relating to energy saving, emissions control, production and application of materials, use of renewable resources towards achieving sustainability. The process of Carbon dioxide ($CO_2$) emission into the atmosphere includes the production of building materials, the construction of a building itself, the exploitation, renovation, possible rehabilitation and its final demolition. Construction industry is intensively growing and actively developing worldwide. In Europe, construction is the largest industrial employer, accounting for 7% of total employment and 28% of industrial employment at least in fifteen European Union (EU) countries (Afolayan, 2001). This sector is however also responsible for such environmental burdens as high energy and water consumption, solid waste generation, global greenhouse gases (GHG) emissions, external and internal pollution and depletion of natural resources. Annually, building construction in the world consumes 25% of the global wood harvest, 40% of stone, sand and gravel, and 16% of water. It generates 50% of global output of GHG and agents of acid rains (Joseph and Tretsiakova-McNally, 2010).

In Nigeria the use of low carbon materials and low carbon construction techniques is indigenous. For example, building earth is the traditional material for construction and has been used for centuries. Extensive research has been carried out in the country, notably by the Nigerian Building and Road Research Institute, and has resulted in the use of stabilized blocks for walling offering low carbon solutions. Model experiments have been carried out in Nigeria with the use of these materials in mass housing projects which include Obasanjo Housing Estate, Ado-Ekiti, the Yankatsari resettlement project, Kano, the Pampomani Housing Estate, Maiduguri and the Low-cost Housing Scheme at Isheri Olofin, Alimosho Local Government Area of Lagos State, Nigeria. The use of interlocking masonry (dry masonry technique) especially for low cost housing for the urban poor in Nigeria has also emerged as research findings on housing sustainability (Olotuah 2002; 2012; Olotuah and Taiwo, 2011; Taiwo et al. 2012).

## 2.0 LITERATURE REVIEW

### 2.1 Housing and Sustainable Building Materials

Housing, which ensures satisfaction, well-being, and productivity of the users and is environment-friendly, is one which takes into consideration key sustainable factors. These factors include: the rational use of natural resources; energy efficiency; elimination or reduction of generated waste; low toxicity; water conservation and affordability. Sustainable building material can offer a set of specific benefits to the owner of a building such as reduced maintenance and replacement costs, energy conservation, improved occupant's health and productivity, lower costs associated with changing space configurations, and greater flexibility in design. The general goal of sustainable development is to meet the essential needs of the present generation while ensuring that future generations have an adequate resources base to meet theirs. It is thus geared towards meeting the needs of the present generation without compromising the ability of future ones to meet their own needs (WCED, 1987). Because housing is central to quality of life and consumes large amounts of resources in its construction, maintenance and use, it contributes significantly to sustainability. Asif, et al. (2007) observed that the building industry consumes 40% of the materials entering the global economy, and is responsible for almost half of the global greenhouse gases. Sustainability is achieved through minimizing climate change, reducing pollution and improving air quality and health, and thus creating sustainable settlements.

Sustainable buildings are prerequisite to the creation of sustainable communities in which people will be happy to live; their needs and aspirations are met without damaging their environment or causing problems for other communities or future generations (McLennan, 2004). For a building to be sustainable, it must respond to the social and economic conditions of the context within which it exists. It also needs to respond to possible future changes in its use which may happen due to different future socio-economic conditions (Sodagar and Fieldson, 2008). The idea of sustainable development involves enhancing the quality of life, thus allowing people to live in a healthy environment, with improved social, economic and environmental conditions (Ortiz et al. 2009).

The operational life of a building is an important factor considering the fact that a significant impact of a building may occur after its construction and installation (Sodagar et al. 2009). An efficient operational life could be ensured with high-performance envelopes, careful selection of materials and good services design. Although operating energy is the majority of energy consumed by buildings, the embodied energy of the materials that compose buildings is an important aspect of the whole life carbon footprint of a building. Embodied energy is the energy used in production and distribution of a product or material. As the operating energy is reduced through efficient design and technology, embodied energy will become more and more important in reducing a building's carbon footprint. Embodied and operational emissions could be reduced by the careful choice of materials and construction techniques (Sodagar et al. 2011).

### 2.2 Sources and Varieties of Low carbon Solid Interlocking Blocks (SIB)

Solid Interlocking blocks (SIB) used in building construction and particularly housing schemes began to gain foothold due to the strong need to accelerate the masonry construction process in the construction industry. The traditional masonry method is labor intensive, and hence slower, due to the presence of a large number of mortar joints (Adedeji, 2011). Anand and Ramamurthy (2003) pointed out the need for further acceleration of the rate of construction occasioned by the elimination of bedding mortar and thereby leading to the development of non-conventional methods of masonry construction techniques, one that adopted special interlocking blocks. Interlocking blocks differ from conventional blocks in that the units are assembled together using geometrical features incorporated in the unit without the aid of mortar.

Varied interlocking blocks developed for use in building constructions include Sparlock system, Meccano system, Sparfil system, Haener system, and the Solid Interlocking blocks which are an improvement over the traditional adobe bricks that were prevalent in the 20$^{th}$ century in some African countries (Anand and Ramamurthy, 2003). Most of the commercially available interlocking blocks vary in geometrical shapes, materials, dimensional characteristics and invariably are proprietary systems. Solid-interlocking blocks were first developed in the USA 1991. And hollow-interlocking block systems were developed as part of the efforts towards improving productivity of conventional and interlocking masonry (Anand and Ramamurthy, 2003).

**Figure 1: Curing and Stacking of Interlocking Blocks**
*Source: Field survey (2011), Obasanjo low-cost housing estate, Ado-Ekiti*

The solid interlocking block of lateritic composition stabilized with cement (Figure 2) was also developed by the Nigerian Building and Road Research Institute, NBRRI (Adedeji, 2007). The main aim of this development was first, to equal or exceed the structural performance of conventional masonry systems and second, to provide a more economical and rational solution for the masonry system thus leading to more competitive designs.

## 3.0 RESEARCH METHODOLOGY

The research involved an innovative mix of research methods including field work and questionnaire survey. The questionnaire collected data on unique projects executed by professionals (architects, engineers and quantity surveyors) using solid interlocking blocks (SIB). The questionnaire designed to investigate 25 variables on housing materials, structured in question form and written in English language, was targeted to elicit responses from clients and professionals in the building industry on the use of the material.

**Table 1: Distribution of Questionnaire within the Study Area**

| S/No | Geopolitical zone | Town | No of Questionnaire | No of Respondents |
|---|---|---|---|---|
| 1 | South West | Lagos | 60 | 48 |
| 2 | North | Abuja | 60 | 38 |
| 3 | South South | Port Harcourt | 60 | 34 |
| 4 | South East | Enugu | 60 | 24 |
| **Total** | | | **240** | **144** |

Field survey, 2011

Data collected includes information on name and address of projects, sizes of buildings in square meters, storey heights of buildings, types of materials used, availability of materials, cost of materials for walling, proficiency of labor in handling materials, number of labor involved in masonry operation, number of hours expended on masonry works, amount paid to a gang of labor on masonry works, estimated man-hour among others for each of the projects. Research assistants, who had earlier been trained by the author, administered the research instrument. Two hundred and forty (240) respondents were randomly selected equally from four geo-political zones in Nigeria out of which one hundred and forty-four responses were collected for analysis.

Secondary data were sourced from government publications, literature, and other publications, existing documentation on housing, environment and sustainable development. Tertiary institutions, research institutes and international bilateral, multilateral and development agencies were contacted to collect published and unpublished materials. Housing and human settlements indicators, alternate indicators, regulatory indicators and alternate regulatory indicators evolved by the World Bank, UN-Habitat, United Nations Development Programme, European research institutes and other development agencies were documented.

## 4.0 FINDINGS AND DISCUSSION OF RESULTS

The main research instruments for data collection were questionnaire, interview schedules and observations from selected case studies. The interview schedule, designed to investigate 25 variables on housing materials, structured in question-form and written in English, was targeted to elicit responses from clients and professionals in the building industry on the use of solid interlocking blocks. The addresses of these professionals were obtained from the Physical Planning Unit of their respective institutions. The selected professionals (architects, engineers, quantity surveyors and builders) commissioned by their institutions to design and supervise the construction of these projects, presented their opinions on the subject. Research assistants, who had earlier been trained by the authors, administered the research instruments and analyzed the results as presented in Table 2 below.

### 4.1 Preference for the use of Stabilized Interlocking Blocks

The tendency towards the preference for the use of interlocking-blocks masonry was investigated when testing the opinions of respondents about the willingness to use these materials. Most of the respondents showed preference for interlocking blocks (83.3%) because of its potential as a low carbon building material. The high preference level of respondents for the material could be based on its overriding advantages over other conventional building materials

**Table 2: Preference for the use of Interlocking Blocks for Housing Construction**

| S/N | Preference level of interlocking blocks | Frequency | Percentage |
|---|---|---|---|
| 1 | Unwilling | 10 | 4.2 |
| 2 | Rarely willing | 30 | 12.5 |
| 3 | Moderately suitable | 40 | 16.7 |
| 4 | Willing | 94 | 39.1 |
| 5 | Very willing | 66 | 27.5 |
| | **Total** | **240** | **100.0** |

*Source: Field survey (2011), obtained from the four selected cities*

Stabilized interlocking masonry is mainly of lateritic soil, which conducts less heat. Users of buildings constructed with the material experiences better indoor thermal comfort in hot and humid regions of Nigeria as compared with the use of sandcrete blocks. This will reduce the use of air conditioners in such buildings. Hence, the operational energy associated with stabilized interlocking masonry houses is substantially reduced. Besides, the material because it is faster in construction of walls, time-saving, use less labor and cost-efficient. The degree of preference for the use of the material will increase as more innovations and confident level of users increases. Hence, the material is strongly recommended for use as an alternative to conventional building materials.

### 4.2 Production Process of Solid Interlocking Blocks

The production process involves five stages viz: soil preparation, preparation of mix, compression of mix, stacking and curing of blocks. In preparing the soil, the satisfactory soil is first sieved in a dry state to obtain a powdery material that can be efficiently mixed with the stabilizer (cement). This could either be achieved manually through the use of a locally constructed sieve of mesh 8 -13 millimeters or through the use of machine in the case of large operations. Soil mixing is done with the use of marked containers such as graduated buckets, head pans, and wheelbarrows to measure the exact quantity of the required material is essential. This could be achieved by volume or by weight. 4-5% of cement is added to the soil, depending on the required strength. Mixing could be done manually or in a pan mixer. For manual work, mixing should be carried out on a hard and clean surface with shovels. Mixture should be determined by ratio of sand or soil-cement-water. Dry components should be mixed first to give a homogeneous mix of uniform color is obtained (say 2-3 times mixing). Water is then slowly added to the mix from a watering can or bucket and mixed for about 2-3 times. The optimal water content of your mix can be estimated with a simple site test known as Ball Test.

The mix is compressed with the use graduated buckets to measure the soil and fill the mould of the machine so as to produce approximately equal sizes of blocks. The hydraulically compressing machine compresses the soil from top and bottom thus resulting in uniform and high density. With 5% cement stabilization and good lateritic soil strength of about 4-5 N/mm² is achieved. The compressed are thereafter stacked and allowed to cure for a week as shown Figure 2.

**Figure 2: Curing process of interlocking blocks**
Source: Field Survey, 2011

**Figure 3: Construction process of interlocking masonry.**

### 4.3 Comparative Advantages of Interlocking Blocks

The research findings show that the development of interlocking blocks (Solid interlocking blocks) has some overriding merits over the conventional types. First, substantial energy savings when compared with other common building materials for construction of buildings. The constructions process does not required expensive burning associated with burnt bricks or engineering bricks with high embodied energy of 8,200 MJ/tons as against that of interlocking blocks of 450 MJ/tons (Table 3). Similarly, the material can be produced on site eliminating energy consumed due to transportation. Cost savings are achieved due to elimination of bedding mortar in the superstructure **(**except in ring beams and in high gables) **a**ccelerates construction, thereby reducing workmanship and cost. In this system freely-available subsoil is the main raw material; the blocks do not require costly burning; transport costs are minimized since block production takes place on site**;** unskilled labor are trained in both block making and building with the material. Besides, speed of construction is a valuable feature of the system, which is much faster than other building methods. **A** mason lays 800 SIB (21 $m^2$ of walling) per day. Moreover, owing to lateritic composition of the material, it is environmentally friendly as blocks are produced under high compression from subsoil, without the need for the fuel-wood used to burn bricks, hence the process is sustainable. Reduction of the pollution caused by the combustion of fossil fuels and cutting down the costs of energy required for manufacturing of the building material are also the main challenges for the producers of highly energy intensive products, like concrete, bricks, plastics and metals.

Carkins, (2009) has also shown that solid interlocking blocks give low carbon solutions because of rational use of natural resources; energy efficiency; elimination or reduction of generated waste; low toxicity; water conservation and affordability. Also, simplicity exemplifies the use of the material. Both the production of blocks and the erection of walls are simple. Relatively unskilled labor may be used to carry out both processes; operating under Hydraform-trained supervision just as excellent thermal capacity (the ability to absorb and hold heat) characterizes the blocks. Solid interlocking blocks are three times as efficient as concrete and almost twice as efficient as fired clay bricks in terms of the thermal insulation they offer. Attractive, face brick finishes (in a variety of natural colors derived from the soil found at individual sites) is also possible with the use of the material. The interior walls may or may not be plastered, painted or sealed.

Table 3 represents data for embodied energy and embodied carbon collected from United Kingdom (UK) and EU sources and worldwide averages of building materials that were used in Nigeria, UK and other countries.

**Table 3: Embodied energy and embodied carbon of common Building Materials**

| S/N | Type of Material (1 ton) | Embodied Energy (MJ/ton) | Embodied Carbon (kg of $CO_2$/ton) |
|---|---|---|---|
| 1 | Limestone | 240 | 12 |
| 2 | Stone/gravel chipping | 300 | 16 |
| 3 | Stabilized Interlocking blocks | 450 | 24 |
| 4 | Soil cement | 850 | 140 |
| 5 | Concrete, unreinforced (strength 20 MPa) | 990 | 134 |
| 6 | Reinforced concrete | 1,810 | 222 |
| 7 | Portland cement, containing 64–73% of slag | 2,350 | 279 |
| 8 | Portland cement, containing 25–35% of fly ashes | 3,450 | 585 |

| | | | |
|---|---|---|---|
| 9 | Local granite | 5,900 | 317 |
| 10 | Engineering brick | 8,200 | |
| 11 | Tiles | 9,000 | 850 |
| 12 | Steel, bar and rod | 19,700 | 430 |
| | | | 1,720 |

*Source: Culled from Sustainability 2, 2010*

Furthermore, solid interlocking blocks demonstrated excellent environmental performance. It can be observed that of is far less than other common building materials available in Nigeria as the total embodied energy of stabilized interlocking blocks was estimated at 450 MJ/ton as opposed to 1,810 MJ/ton for the reinforced concrete or Portland cement with slag 2,350 MJ/ton, while an equivalent output of $CO_2$ emission was 24 kg $CO_2$/ton compared to 202 kg $CO_2$/ton for traditional bricks in mainstream construction (Table 3).

## 5.0 RECOMMENDATIONS AND CONCLUSION

The philosophy of sustainable development can be said not only a question of designing for energy efficiency. One of the basic principles of sustainable development is that it should work with and not against nature. It should aim to achieve the maximum use of ambient energy sources in the creation of internal environments that are, as far as possible, naturally sustained. It is important to realize that in order to achieve a sustainable architecture, an integrated approach to design is required and appropriate design strategies must be formulated at the outset. Sustainable architecture should be logical in its use of technology. Technology must be subservient to design and not a goal. While some buildings may use low-tech solutions to achieve their goals, intelligent systems and elements may require specification under special circumstances. For a building to be sustainable, it must respond to the social and economic conditions of the context within which it exists. It also needs to respond to possible future changes in its use which may happen due to different future socio-economic conditions. A building therefore should be flexible and adaptable. The use of building materials sourced locally can help lessen the environmental burdens. This would considerably cut transportation costs and provide support of the local economies. Also, it is quite important to take into account an inherent durability and quality of building materials and increase them as much as possible. In addition, materials and components should have a good recycling potential (Halliday, 2008).

This paper has shown that the use of stabilized interlocking blocks can offer low carbon solutions in construction. Stabilized interlocking blocks have low embodied energy in comparison with other conventional building materials. They are therefore useful for the development of sustainable housing in Nigeria.

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# RECYLCED ASPHALT PAVEMENT AS COURSE AGGREGRATE REPLACEMENT IN HIGH STRENGTH CONCRETE MIXES

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## ABSTRACT

Many new construction materials utilizing recycled or bi-product waste have recently been developed to help create "greener" construction. One of these materials utilizes recycled asphalt pavement (RAP) as a replacement for a portion of the course aggregate in concrete mixes. Previous studies on these concrete mixtures has shown that the RAP inclusion considerably lowers the compressive strength of the concrete; thus limiting its usefulness. However, the inclusion of RAP in high strength concrete mixes has yet to be studied. Additionally, most of the previous studies have replaced the course aggregate only by weight and not by weight and gradation and have taken the RAP from only one source. This study considers several factors that may affect the strength of concrete mixes that utilize RAP as course aggregate replacement. First, the variability in compression strength is studied to determine if geography and environmental conditions of the RAP harvest location affects the mechanical properties. Then, six separate RAP replacement percentages are studied to determine an ideal replacement amount and the relationship between RAP replacement to compressive and tensile strength. This study also presents the results of gradated versus non-gradated RAP replacement in high strength concrete mix.

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## INTRODUCTION

Portland Cement Concrete (PCC) is a key building material in bridges, buildings, parking garages, foundations, retaining walls as well as other construction and structural applications. It is a reliable and useful construction material that is often utilized for its compression strength and durability. Concrete is especially useful in areas where saturation or water is prevalent due to its ability to withstand chemical and radiological exposure. Many recycled or bi-product waste materials have recently been utilized to create “greener” concrete construction materials. The concept of re-using and recycling our construction materials is becoming increasingly popular as our understanding of the daily consumption use of natural resources is having on the environment. (Construction Materials Recycling, 2012).

One of the materials utilized to create “greener” concrete is recycled asphalt pavement (RAP), which is used as a replacement for a portion of the course aggregate in the concrete mix. Previous studies on these concrete mixtures has shown that the RAP inclusion considerably lowers the compressive strength of the concrete; thus limiting its usefulness (Delwar et Al., 1997a). However, the inclusion of RAP in high strength concrete mixes and the variability of strength of RAP due to location have yet to be studied. Additionally, most of the previous studies have replaced the course aggregate only by weight and not by weight and gradation and have taken the RAP from only one source (Delwar et Al., 1997b).

## METHODOLOGY

The three main objectives of this study are:

1) Determine the variability in the compressive strength between RAP concrete utilizing gradated RAP versus non-gradated.
2) Determine the variability in the compressive strength of RAP concrete utilizing gradated RAP from five different RAP harvest locations around the state of Idaho.
3) Determine the variability in the compressive strength of RAP concrete utilizing varying replacement percentages of RAP for the course aggregate.

In order to study the objectives of this study, concrete samples for both compression and split tensile testing, corresponding to the three objectives, are constructed and tested in the Materials Laboratory at Idaho State University. The RAP and course aggregate are gradated according to ASTM D6913, “Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis”. The concrete mixes are prepared and compacted in 4” diameter by x 8” high cylinder molds for compression testing, and 6” diameter by 12” high cylinder molds for split tensile testing according to ASTM C192-90, “Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory”. Five 4” x 8” cylinders and three 6” x 12” cylinders are made for each batch of concrete tested. The samples are cured for 28 days in a water bath storage container according to design standard ASTM C511-09 “Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the

Testing of Hydraulic Cements and Concretes" and then tested according to ASTM C39/C39M-12, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens" as well as ASTM C496/C496M-11, "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens". (ACI 318-05, 2012)

For the RAP gradated versus non-gradated, two harvest location RAP samples are chosen to be tested for both sieved and non-sieved compression strength; Wilder and Pocatello (see Figure 1). High strength PCC is made with a 35% replacement of RAP for the course aggregate. A sieve analysis was completed for each individual location on the RAP. The data was collected and compared below in Figure 1.

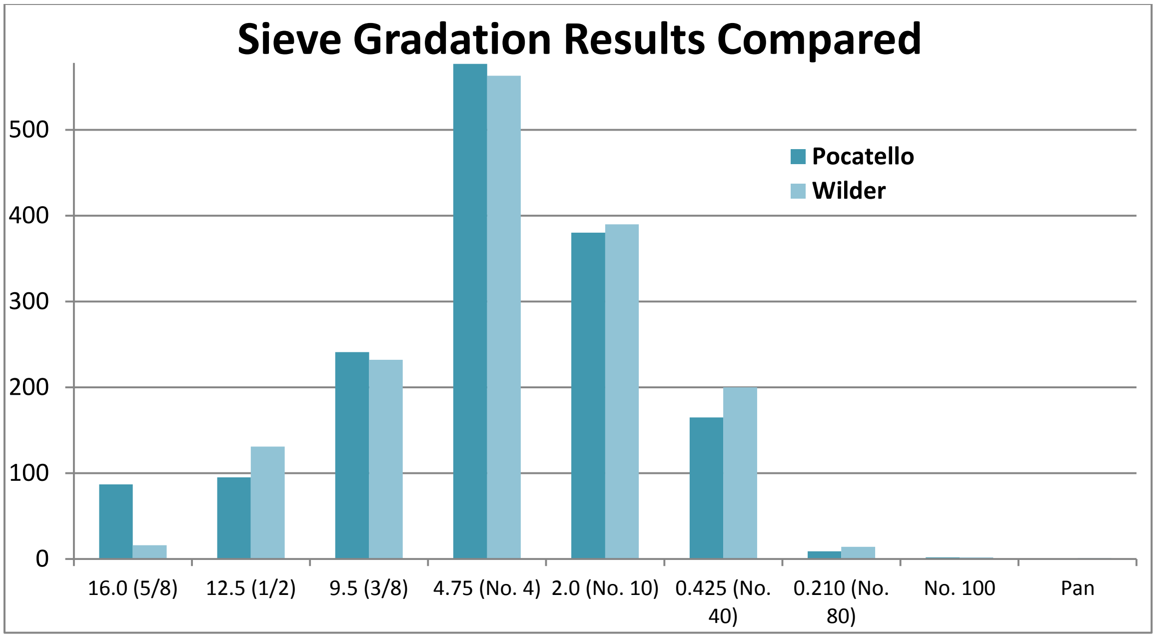


**Figure 1. Sieve Gradation Results Compared**

For the RAP harvest location variability study, RAP is collected from five locations throughout the state of Idaho; Bear Lake, Coeur d'Alene, Dubois, Pocatello and Wilder (see Figure 3). The RAP is gradated to match the gradation of the course aggregate used in the mix design. The mix design used is a high strength concrete design designed to break at 7,000 psi or greater. Due to the high strength design mix used, a super plasticizer is used in order to achieve necessary workability. Course and fine aggregate from local suppliers is also used. Type II Portland Cement and Type "F" fly ash was used in order to replicate a more widely used design mix. The RAP from each location is then used to replace 35% of the course aggregate in the high strength PCC (HSPCC) mix. After the 28 day water bath cure, compression tests are administered. The data from the testing is collected and compared to geological and traffic information for each location.

In order to study the effect that varying the RAP course aggregate replacement percentage has on compressive strength, five sample batches of HSPCC with varying percentage of RAP replacement of the course aggregate are prepared and tested. The first batch starts at 25% RAP replacement and increases in 5% increments up to 50%.

Additionally, a control batch with no RAP replacement is prepared for comparison. These batches are each tested for both compression as well as tensile strength.

## RESULTS

### *RAP Gradated versus Non-Gradated*

The laboratory test results for the gradated versus non-gradated RAP replacement in HSPCC are recorded and shown below in Table 1.

**Table 1. RAP Gradated and Non-Gradated Compression Average Compressive Strengths (psi) for a 35% RAP Replacement HSPCC Mix**

| IDAHO LOCATION | AVERAGE COMPRESSIVE STRENGTH (PSI) | |
|---|---|---|
| | Gradated | Non-Gradated |
| Pocatello | 3966 | 4265 |
| Wilder | 5598 | 4977 |

The results of the compression tests shown in Table 1 demonstrate that there is a difference in compressive strength if the RAP is sieved and gradated versus not sieved and gradated. However, based on the fact that one gradated sample has a lower compressive strength than the non-gradated and for the other sample the inverse is true, no direct conclusion about the effect of gradation on compressive strength can be made. The RAP harvesting techniques and storage varies from location to location and therefore not all RAP from various locations would provide consistent results which is necessary to provide quality controlled concrete products. Figure 2 shows the large variability that can occur due to different harvesting techniques.

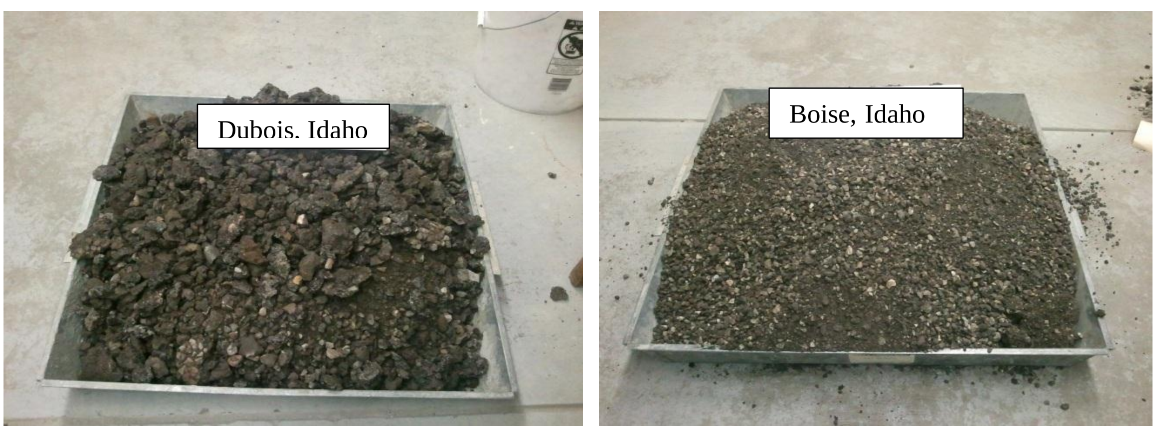


**Figure 2. RAP Harvesting Variability**

### *RAP Location Variability*

The 35% replacement RAP HSPCC samples for each of the five locations as well as the control batch are tested and the average measured compressive strengths are shown in Table 2. When sieving the Boise, Idaho Harvest Location, the RAP was so finely ground at harvesting; the entire RAP fell through the No 100 sieve, the smallest sieve used and therefore could not be gradated appropriately to replace the correct percentage of aggregate with the appropriate size of RAP. Due to the large variability of the harvest on the Boise RAP, the results were documented but not compared to the other RAP locations.

**Table 2. RAP Location Average Compression Strengths (psi) for a 35% RAP Replacement HSPCC Mix**

| IDAHO LOCATION | COMPRESSIVE STRENGTH AVERAGE (PSI) |
|---|---|
| CONTROL | 7041 |
| BOISE | 5743 |
| COURDELANE | 4337 |
| BEAR LAKE | 4357 |
| POCATELLO | 3966 |
| WILDER | 5598 |
| DUBOIS | 4325 |
| ***AVERAGE/STANDARD DEVIATION*** | ***5053/1113*** |

The results from Table 2 are shown in Figure 3 below. You can see that by using a gradated RAP in the HSPCC, we can eliminate the variability that occurs by using RAP from different harvesting locations.

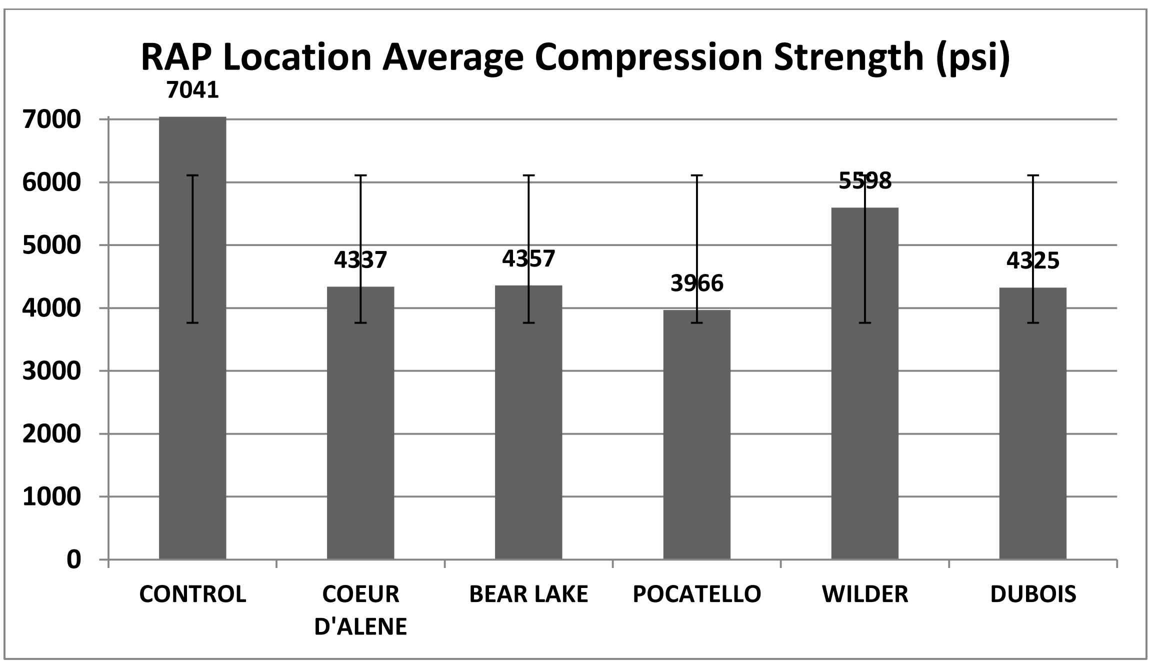


**Figure 3. RAP Location Average Compression Strength**

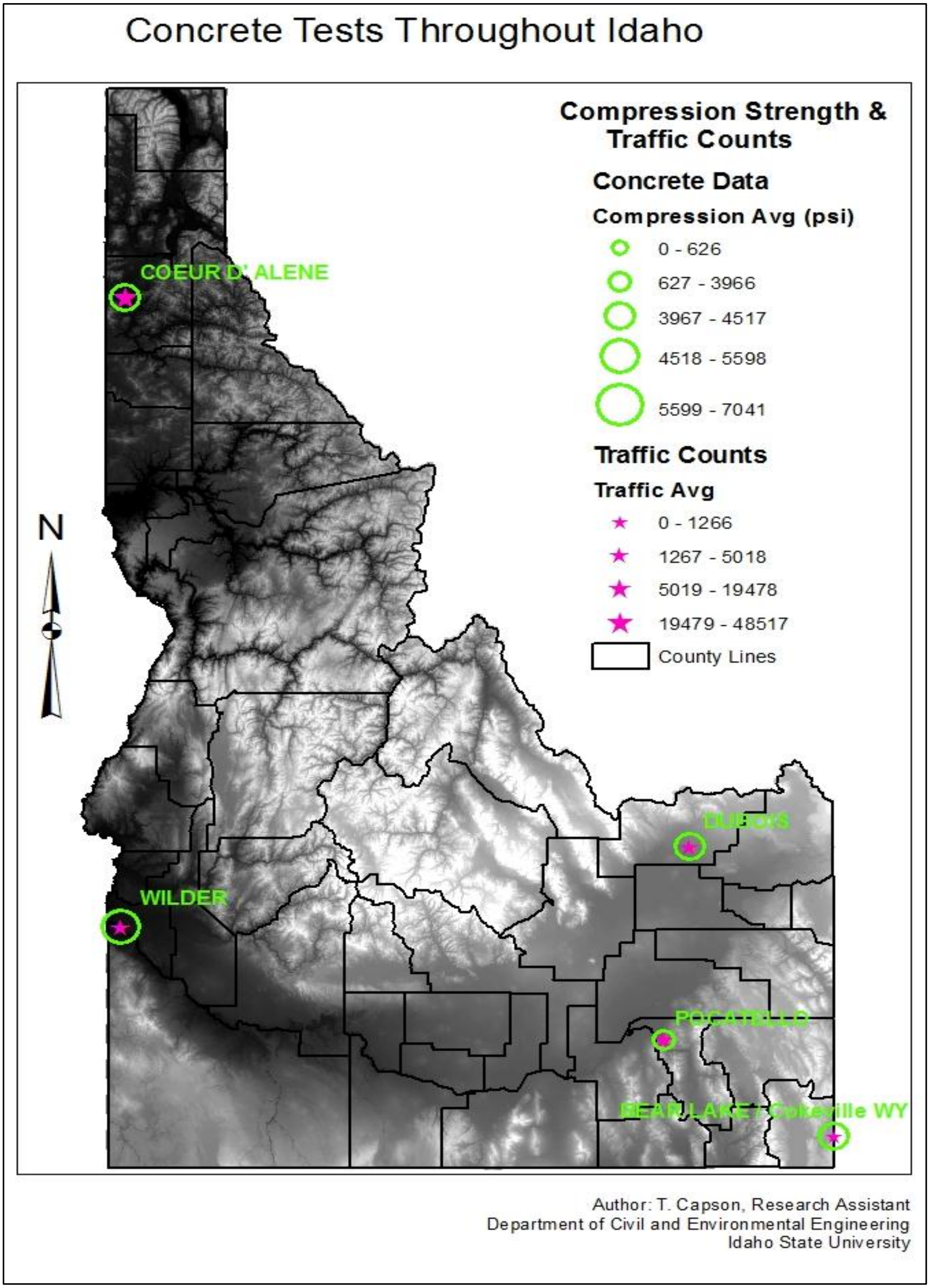


**Figure 4. RAP Harvest Locations with Corresponding Average Compression Strengths (psi) for a 35% RAP Replacement HSPCC Mix and Traffic Counts**

The tests results from the lab are also compared at each individual location to the following information for location from which the RAP was harvested: winter precipitation, yearly precipitation, elevation, and traffic counts (Idaho Department of Transportation, 2012). The data is plotted and analyzed using ARC Map 10 and the results are shown in Figure 4. Table 2 and Figure 4 show that a direct correlation to the amount of traffic in an area and the corresponding average compression strength of the RAP HSPCC exists. The more traffic the area receives, the weaker compressive strength wise the concrete is. This factor may be attributed to the fatigue of the pavement materials during their service life resulting in less required stress levels to crack the asphalt paving aggregate as shown in Figure 4. The analysis also showed that no apparent relationships exist between the average compressive strength and the annual precipitations or elevation.

**Figure 5. Compression Cylinder Breaks; RAP Cylinder (left), Control Batch (right)**

***RAP Replacement Percentages***

The samples for the various RAP replacement percentages are tested in both compression and tension and the results recorded and shown in Table 3.

**Table 3. Average Compression & Tensile Strength for Varying RAP Replacement Percentages Using Pocatello RAP**

| POCATELLO RAP REPLACEMENT (%) | TENSILE STRENGTH AVERAGE (PSI) | COMPRESSION STRENGTH AVERAGE (PSI) | COMPRESSION REDUCTION FROM CONTOL BATCH |
|---|---|---|---|
| CONTROL | 579 | 7041 | - |
| 25 | 526 | 6003 | 15% |
| 30 | 628 | 5291 | 25% |
| 35 | 443 | 3966 | 44% |

| | | | |
|---|---|---|---|
| 40 | 497 | 4867 | 31% |
| 45 | 491 | 4770 | 32% |
| 50 | 496 | 4511 | 36% |

As expected from the results of previously published studies, the results from the laboratory tests show that the RAP inclusion does decrease the compressive strength in concrete mixes (Skourup and Erdogmus, 2010). However, by utilizing a HSPCC mix, a compressive strength of 4500 psi or greater was maintained with all RAP replacement percentages except for the 35% replacement percentage. This anomaly may be attributed to the fact that the 35% replacement mix was cast at a different time (the same time as the varying location study) than the other percentage replacement mixes. As this study is ongoing, additional studies are being carried out to determine if this is in fact the case or if for some reason a 35% replacement mix behaves differently. Despite this one anomaly, the fact that by using a HSPCC mix, a fifty percent RAP replacement for course aggregate can be done and still achieve a compressive strength of 4500 psi, demonstrates that a useable RAP concrete mix can be produced. From the tests results, no apparent direct correlation between the tensile strength results and the RAP percentage replacement exists. However, by comparing the RAP results to the control batch, it can be determined that utilizing the RAP as replacement does not adversely affect the tensile capacity of the concrete.

If the results from Table 3 are plotted with the 35% mix excluded (see Figure 6), it can be seen that a negative linear relationship between the RAP replacement percentage and the average compressive strength exists. From the plot an equation can therefore be developed which can be used to predict the compressive strength based on a proposed RAP replacement percentage. This allows mix designers to carry out cost/benefit analysis of utilizing RAP in their designs and to leverage that against green design requirements. The linear equation developed is $y = -53.74x + 7130.6$. This shows that the decrease in compressive strength is almost 54 psi for every percent of RAP added to the design mix.

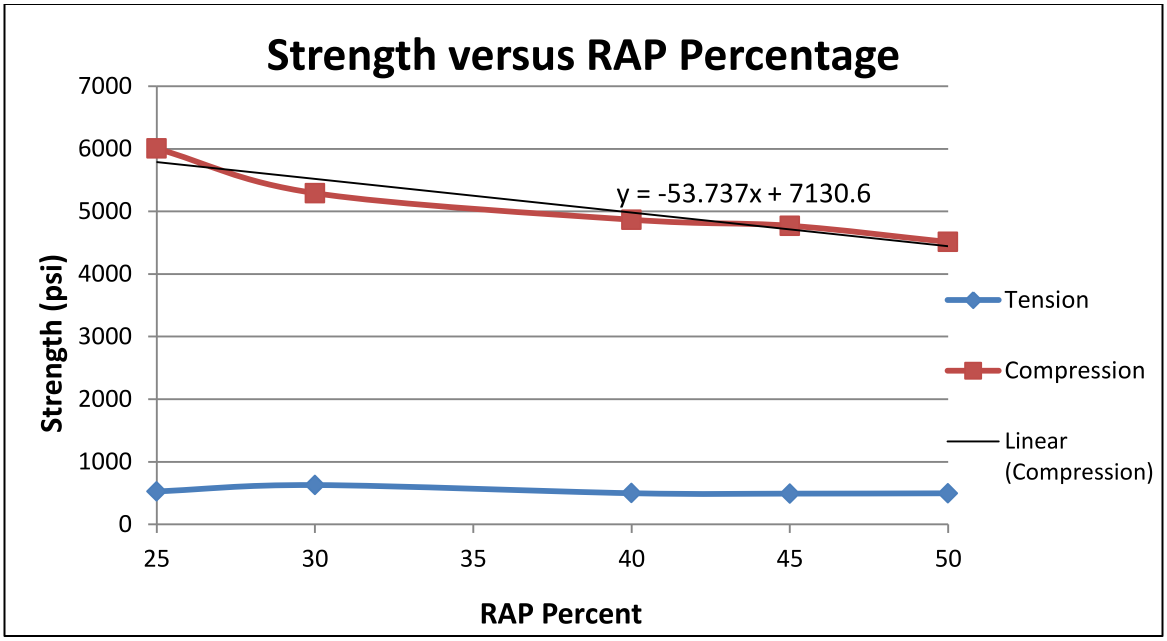


**Figure 6. Average Compression & Tensile Strength (psi) for Various RAP Replacement Percentages**

## CONCLUSIONS AND FUTURE WORK

A method for producing useable compressive strength concrete that utilizes RAP as a percentage replacement for course aggregate in HSPCC has been provided in this study. Results conclude that it is feasible to have a greener mix design of concrete using RAP as a replacement of course aggregate while maintaining strength in concrete that is strong enough to be utilized in structural applications. Sieving the RAP into the appropriate gradations directly affects the strength of the concrete and in order to control the outcome of the concrete mix, sieve gradations must be performed and replaced at the appropriate percentage to match the course aggregate the RAP is replacing.

It is also evident from this study that the traffic count from the RAP harvesting location effects the compressive strength of the concrete; the more traffic on the road the RAP is harvested from, the lower the compressive strength of the concrete. Location may still be a factor on the RAP strength and warrants further study as does the type of de-icing techniques used on the road which was not considered in this study. Further studies would need to be conducted in order to prove the effects that location has on the strength of the RAP in the concrete.

Further studies need to be conducted in replacing the fine aggregate with RAP as well as replacing a mixture of both the fine and course aggregate of RAP. Percentages with mixtures needs to be considered and further research can be done on mix and design when using RAP as a replacement in all types of concrete, not just HSPCC.

Finally, while this study showed that it is possible to produce structural viable RAP concrete mixes; further study needs to be conducted on the durability and long term performance of these mixes.

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# EFFECT OF SPENT CATALYST AS A FINE AGGREGATE ON THE PROPERTIES OF CONCRETE

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## ABSTRACT

Spent catalyst is a by-product generated by oil refineries. There are two types of spent catalysts produced from oil refineries in Oman; Zeolite catalyst generated at Sohar Refinery and Equilibrium catalyst generated at Mina Al-Fahl Refinery. Spent catalyst can be used in concrete applications due to its pozzolanic nature. This study investigates the potential use of spent catalysts in concrete as partial substitute of sand at w/c ratios of 0.5 and 0.7. Concrete mixtures with different proportions of spent catalyst (up to 25% as sand repalcement) were prepared. Concrete mixtures were evaluated for compressive strength, setting time, water absorption, and corrosion resistance. The results showed that using 25% of the Sohar refinery's spent catalyst as sand replacement gave 73% increase in the cubes compressive strength at w/c ratio of 0.7. However, using spent catalyst from Mina Al-Fahl Refinery as sand replacement decreases the compressive strength gradually with the increase of spent catalyst percentage. The results also indicated that the elapsed time decreased as the quantity of spent catalyst from both refineries increases. Negligible increase in the total water absorption was observed in concrete when both spent catalysts were used. Concrete specimens made with spent catalyst from Sohar Refinery showed good corrosion resistance than the control mixture whereas spent catalyst from Mina Al-Fahl Refinery accelerated the corrosion process.

Keywords: Concrete; Spent Catalyst; Sand, Cementitious Material; Zeolite, Fine Aggregates

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## INTRODUCTION

Two types of spent catalysts are generated from oil refineries in Oman. Zeolite catalyst produced from Sohar Refinery which is powder in nature with a mean size of 0.097 mm and Equilibrium spent catalyst generated from Mina Al-Fahl Refinery with spherical shape and a mean diameter of 3.5 mm. In October 2011, the accumulated spent catalyst from Sohar Refinery that was stored in the dumping site was more than 25,000 tons. Moreover, it is estimated that the daily production of spent catalyst is about 20 tons per day. This large quantity of the spent catalyst creates an environmental problem. Therefore, this study investigates the potential use of spent catalysts in concrete as partial substitutes of sand. Studies conducted on spent catalysts confirmed their pozzolanic nature. Pacewska et al. (1998) reported that the pozzolanic activity depends on the size of the particles whereas Ahmadi et al. (2010) and Antiohos et al. (2007) suggested that the pozzolanic activity of spent catalyst depends on the chemical composition and on the specific surface of the material. Monzo et al. (2004), Pacewska et al. (1998) and Rattanasak et al. (2001) found that using spent catalyst as sand replacement enhanced the bonding strength in concrete due to the formation of hydrated calcium silicates and aluminate at the boundary zones. The pozzolanic activity of the Equilibrium spent catalyst was improved by crushing the spent catalyst to finer sizes and by calcination up to 650 ˚C [Tseng et al. 2005].

Since spent catalyst is finer than sand, the concrete setting will decrease by increasing the percentage of the spent catalyst in the mixture. However, the hydration process is accelerated and the setting time is reduced due to the rapid conversion of $Ca(OH)^-$ to aluminosilicate gel [Pacewska et al. 1998]. Pacewska et al. (1998) also reported that the water absorption decreased slightly by using the spent catalyst as sand replacement.

Antiohos et al. (2006) found that spent catalysts have some traces of heavy metals like Ni, Cd, V, etc. in small concentrations. However, Sun (2003) concluded that these metals will be encapsulated by the matrix. Ampadu et al. (2007) and Pacewska et al. (2002) confirmed that spent catalyst can have safe applications in concrete since the heavy metals grains will be solidified by the hydration process.

## MATERIALS

Specific gravity of spent catalyst from Sohar and Mina Al-Fahl Refineries was determined in accordance with ASTM D854 to be 2.60 and 2.79, respectively. $SiO_2$, $Al_2O_3$ and $Fe_2O_3$ represent 77% and 68% of the chemical of Sohar and Mina Al-Fahl spent catalysts, respectively. Spent catalyst from Sohar Refinery was used as received whereas the spent catalyst from Mina Al-Fahl Refinery was crushed to pass sieve size 2.36 mm.

Aggregates used in concrete mixtures were brought from local crushers. Specific gravity for the 20 mm, 10 mm and the fine aggregates was 2.79, 2.74 and 2.85, respectively.

Cement used in the study was ordinary Portland cement.

## EXPERIMENTAL PROGRAM

Two water-to-cement ratios were considered: 0.5 and 0.7. Spent catalyst from Sohar and Mina Al-Fahl Refineries were used. Sand was replaced by spent catalyst in an increment of 5%; starting by the control mixture with 0% of spent catalyst up to 25%. Each mixture has an ID designation consists of two characters and three digits, the first character; S or M; indicates the source of the spent catalyst, where "S" is for Sohar Refinery and "M" is for Mina Al-Fahl Refinery. The second character "S" is referring to the replaced material; sand replacement. The first digit; 5 or 7; referred to the water-to-cement ratio and the last two digits show the replaced percentage of sand by spent catalyst.
Superplasticizer was used for mixtures with 25% spent catalyst substitution in order to produce workable concrete during casting as shown in Table 1.

Table 1 Superplasticizer dose

| Mixture ID | SS525 | SS725 | MS525 | MS725 |
|---|---|---|---|---|
| Dose % | 2.0 | 2.5 | 1.5 | 2.0 |

The testing program includes cube compressive strength at 7 and 28 days of curing, total water absorption test, corrosion test and setting time test. Cube compressive strength test was conducted in accordance with BS 1881: Part 116 using a loading rate of 5.625 kN/s. Total absorption test was conducted in accordance with ASTM C642 and setting time in accordance with ASTM C403. Corrosion test was conducted by casting three cylinders with 100 mm diameter and depth of 300 mm with 8 mm steel bar inserted in each cylinder. They were tested by immersing the reinforced cylinders in 3% NaCl solution to a depth of 200 mm, a current of 40 mA and a voltage of 6 volts were applied until cracks appear in the sample.
Setting time, corrosion and total water absorption tests were conducted for the control mix, 15% and 25% spent catalyst at both w/c ratios and for both types of the spent catalyst.

## RESULTS AND DISCUSSION

### Compressive Strength

Figure 1 shows the average compressive strength of concrete at 7 days of curing. Results show that the compressive strength increased by increasing the quantity of spent catalyst from Sohar Refinery. There was 10% and 50% increase in the compressive strength of concrete at 25% sand replacement and w/c ratios of 0.5 and 0.7, respectively. This enhancement in the compressive strength may be attributed to the high pozzolanic activity of the spent catalyst from Sohar Refinery. However, using crushed spent catalyst from Mina Al-Fahl Refinery as sand replacement showed gradual reduction in the compressive strength. There was about 50% decrease in the compressive strength at 25% spent catalyst replacement compared with the control mixture. The presence of high percentage of aluminates (66.7%) and low percentage silicates (1.7%) as well as the difference in the grain strength may be the main cause in the decrease of the strength with the increase of Mina Al-Fahl spent catalyst substitution.

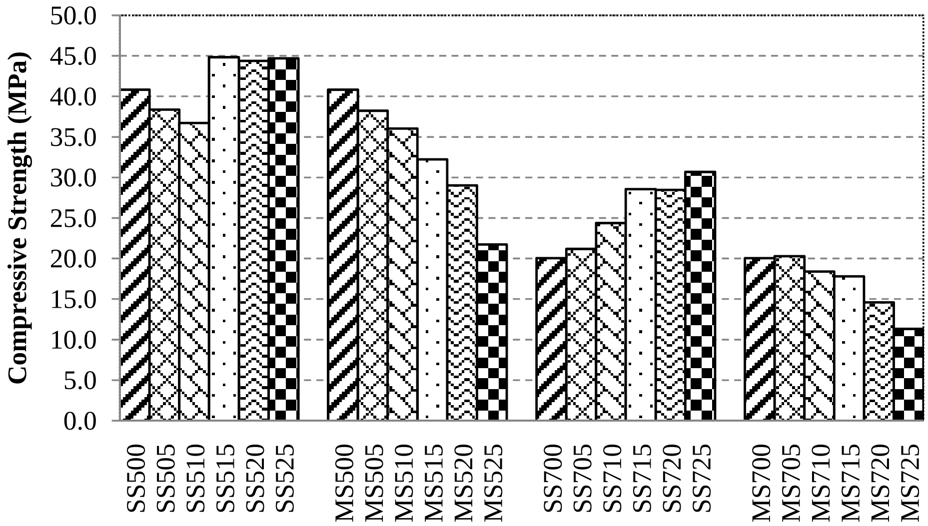


Figure 1 Cube compressive strength after 7 days curing

Figure 2 shows the average compressive strength of concrete made with spent catalyst at 28 days of curing. It can be seen from Figure 2 that use of spent catalyst from Sohar Refinery yielded better results than spent catalyst from Mina Al-Fahl Refinery. For mixtures prepared with 25% of Sohar Refinery spent catalyst at w/c ratio of 0.7, there was 73% improvement in the compressive strength compared with the control mixture whereas there was about 46% decrease in the strength for concrete mixture made with Min Al-Fahl Refinery spent catalyst at both w/c ratios.

The relative strength of the cubes (ratio of 7 days to 28 days) is shown in Figure 3. Figure 3 shows that spent catalyst from Sohar Refinery gave lower early strength compared to the spent catalyst from Mina Al-Fahl Refinery. This was because spent catalyst from Mina Al-Fahl Refinery contains high amounts of aluminates. Replacement of more quantities of spent catalyst in lieu of sand causes decrease in the development of strength at early ages. This decrease was higher in mixture with w/c of 0.7. The same trend was observed in concrete mixtures made with spent catalyst from Mina Al-Fahl Refinery.

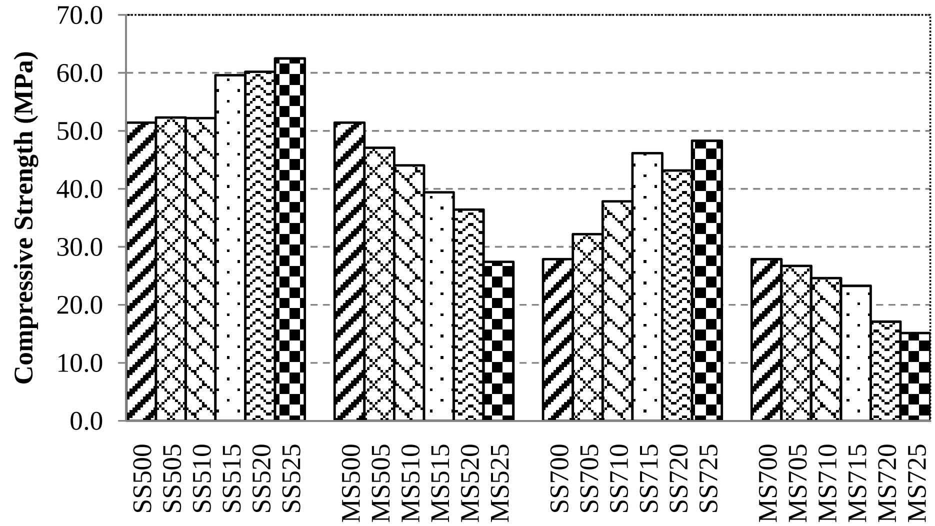


Figure 2 Cube compressive strength after 28 days curing

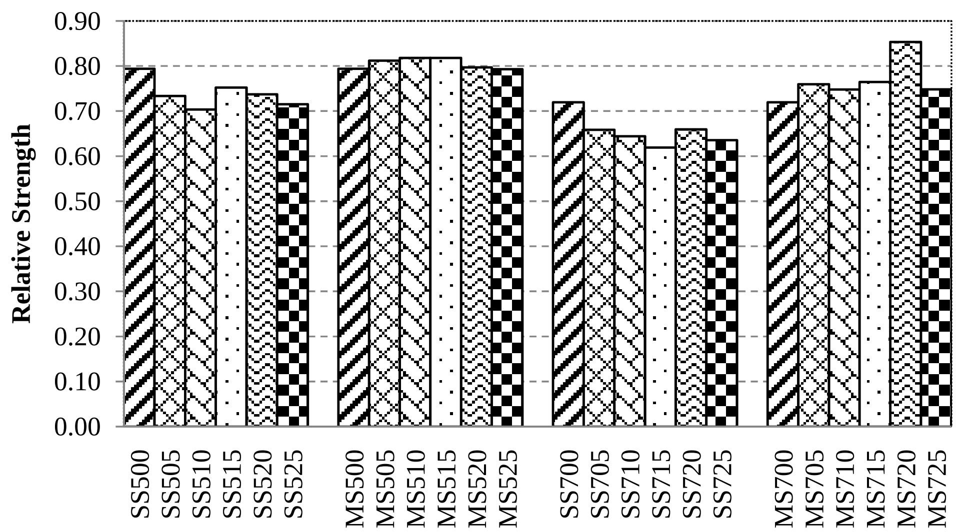


Figure 3 Relative compressive strength 7/28 days

**Setting Time**

The initial and final setting times were recorded at 3.5 MPa and 27.6 MPa; in accordance with ASTM C403, respectively. Results presented in Figure 4 indicate that there was a decrease in the elapsed time with the increase of spent catalyst content in the concrete mixtures. The final setting time of the control mixture at w/c ratio of 0.5 was 389 minutes while the elapsed time decreased to 337 minutes when 15% of the spent catalyst was used. Concrete mixtures with 25% spent catalyst took more time to reach the final setting than concrete mixtures with 15% spent catalyst due to the use of the superplasticizer in these mixes. In general mixtures made with the spent catalyst from

Mina Al-Fahl Refinery require less setting time than the mixtures made with spent catalyst from Sohar Refinery.

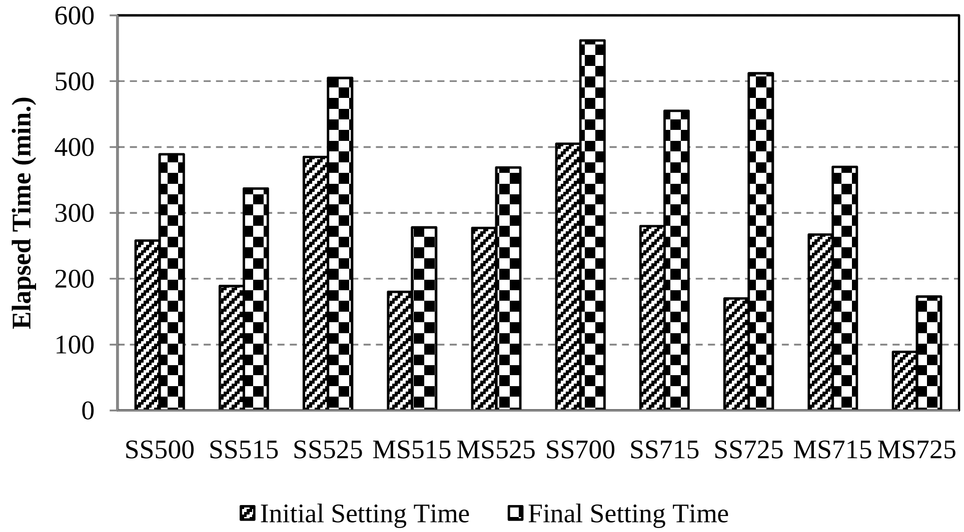


Figure 4 Initial and final setting time

**Total Absorption**

Three portions from three different concrete samples were cut for total absorption test in accordance with ASTM C642-97. Results in Figure 5 show that the total water absorption increases by increasing the w/c ratio and the replacement percentages of the spent catalyst from both refineries. Concrete made with spent catalyst from Sohar Refinery showed less water absorption than concrete made with spent catalyst from Mina Al-Fahl Refinery. At 25% replacement of Mina Al-Fahl spent catalyst at both w/c ratios; MS525 and MS725; the volume of the pores was high due to poor compaction during the casting since the mixtures were dry.

**Corrosion**

Use of spent catalyst from Sohar Refinery as sand replacement increases the corrosion resistance as shown in Figure 6. Figure 6 shows that steel in the control sample started to corrode after 14 days. The samples showed good corrosion resistance as the replaced spent catalyst quantity increased in concrete mixtures. This was because of powder nature of the spent catalyst which works to close pore holes in the specimen [Ahmadi and Shekarchi 2010, Pacewska et al. 2002]. Concrete samples with w/c ratio of 0.7 showed less corrosion resistance than concrete samples with w/c ratio of 0.5. Concrete samples made with 25% of Mina Al-Fahl spent catalyst experienced very low corrosion resistance where samples started to crack and reinforcement corroded after 3 days of testing.

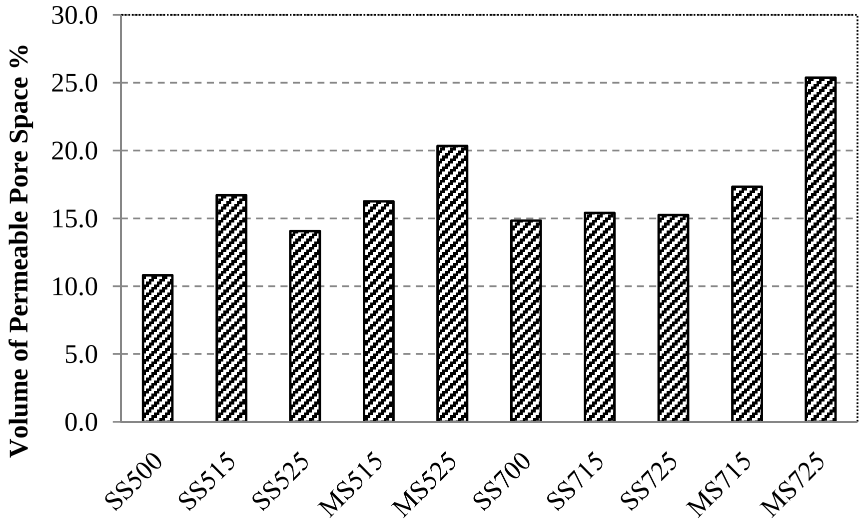


Figure 5 Effect of spent catalyst on the total absorption

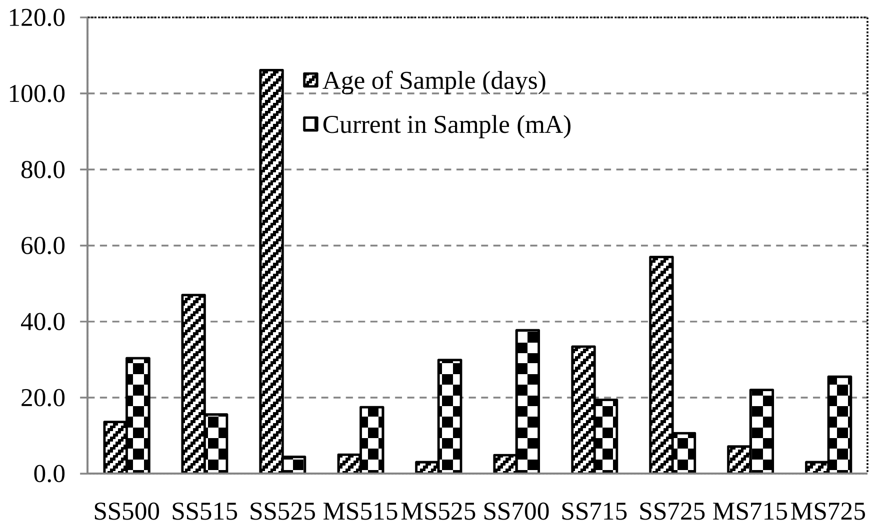


Figure 6 Effect of the spent catalyst on the steel corrosion

## CONCLUSIONS

Form the study conducted on the use of spent catalyst as sand replacement in concrete it can be concluded that using 25% of the Sohar refinery's spent catalyst as sand replacement gave 73% increase in the cubes compressive strength at w/c ratio of 0.7. The results also indicated that the elapsed time decreased as the quantity of spent catalyst from both refineries increased. Negligible increase in the total water absorption was observed in concrete when both spent catalysts were used. Concrete specimens made with spent catalyst from Sohar Refinery showed good corrosion resistance than the control mixture whereas spent catalyst from Mina Al-Fahl Refinery accelerated the corrosion process.

## ACKNOWLEDGEMENTS

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# CHALLENGES AND OPPORTUNITIES IN INVOLVING FACILITIES MANAGEMENT IN DATA HANDOVER: LONDON 2012 CASE STUDY

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## ABSTRACT

There is an increasing interest of the usage of project data for the life-cycle with the evolution of Building Information Modelling, which promotes the incremental collection of data. This research considers the role of facilities management in developing data for handover at project completion by empirically studying the delivery of the London 2012 games. Eighteen interviews were conducted with project participants. Backgrounds of participants included project sponsors (client representative), delivery partners and facility manager professionals. Our findings suggest a number of approaches taken by a client for the transition of knowledge into the practices of facilities management. These approaches are 1) creating a culture for knowledge transfer in the project; 2) strategic knowledge transfer through guides and processes; 3) knowledge transfer through social interactions; 4) knowledge transfer through the representation of facilities management. There were a number of enablers identified that were aimed at progressing knowledge transfer into facilities management in the project to different degrees such as a transition phase for data handover of up to 6 months in projects. However, there were challenges that limited knowledge transfer as end-user links with the project came to an end with project completion. The contribution of this paper outlines how the client can involve facilities management professionals in the project through incorporating their knowledge during the data handover phase. However, this does not have to be one way and the implications of this study is that having a project representative after the data is handed over to the end user will further enable knowledge transfer from projects into facilities management practices.

**Keywords:** Data handover, Client, Facilities Management and Knowledge transfer

## INTRODUCTION

The activities of Facilities Management (FM) are diverse and require different data to meet the need of each activity. The activities involve asset management; maintenance planning; work-space management (Atkin and Brooks, 2000, Finch, 2004, Bainbridge and Finch, 2009, Noor and Pitt, 2009, Becerik-Gerber et al., 2012). There are challenges of obtaining data from projects into use in FM as often the practices in these contexts do not connect though research in knowledge transfer argue it is better to involve the end user (Brown and Duguid, 2001). The client is the primary link between the project and the FM professionals after handover and indeed sets the requirements of what data is to be delivered at the end of the project. There is a growing interest in obtaining data from construction/infrastructure projects with Building Information Modelling (BIM) that incrementally build data throughout the building life-cycle (Bew and Underwood, 2010, Jordani, 2010). There are a number of execution plans that view FM as part of the process for delivery and identify how the data from BIM could be used within different FM activities, but the actual execution of the plan take FM activities as a whole (GSA, 2011, Messner et al., 2012). While literature on the use of BIM in FM consider the potential value (Becerik-Gerber, 2010, Becerik-Gerber et al., 2012, Arayici et al., 2012, Ebinger and Madritshc, 2012, Shen et al., 2012), there is a focus on the technological aspects of BIM and less of a focus on the processes of involving FM for project delivery.

This work extends on the trajectory of BIM research by looking at the project client's role in transferring knowledge from the project to FM on a particular project – the London 2012 Olympics. The London 2012 Olympics is an extreme case, with a fixed deadline. The data went into use for FM practices as soon as projects were delivered. The opening ceremony was to be watched by millions so there was a sense that, on the 27th July 2012, the world would be examining the outcome of seven years of work and there was no time for errors. In this way the projects of London 2012 are useful to consider the enablers and disablers of knowledge transfer from projects into FM.

There cannot be an assumption that practices of FM will adapt to digital data used in the project. However, the client can develop digital data that suit current FM practices through thinking beyond the project scope and viewing FM as part of the project rather than the next stage. This work contributes in considering the client's role in representing FM requirements in projects right up until the data is handed over but proposes that this role, or a similar one, could be extended after the data is handed over to continue knowledge transfer from projects into FM practices.

## LITERATURE

The rationale of using BIM is for the ongoing life-cycle of the building. There are a number of ways in which BIM can be used in FM activities such as in locating components, supporting maintainability studies and controlling and monitoring energy and therefore, BIM should be viewed as a building asset (Becerik-Gerber et al., 2012). BIM is delivered and developed in the project, often without the involvement of FM, where the client must represent the requirements. Becerik-Geber et al., (2012) argue that the client must be visionary as data requirements are usually determined by the client at the design stage and finalised at the procurement and construction stages and in this sense the client is a controlling agent for leveraging BIM in FM. However, there is some evidence to suggest that in the UK, the take-up of information technologies such as that of computer aided facilities management is quite diverse and implemented more in dedicated service providers than in an in-house FM with less of a likelihood of medium sized enterprises (Bainbridge and Finch, 2009). While there are challenges in the take up of information technologies within FM practices, the focus here is on the challenges of handover of digital data for knowledge transfer from projects to FM.

The client outlines the requirements for delivery but FM remain disconnected to the project (Whyte et al., Forthcoming). The knowledge management literature argues that 'useful knowledge' is best developed by members of the community of practice who directly benefit from it as practices are quite distinct and have different assumptions and perspectives about the world (Brown and Duguid, 2001 p.201-5). Having FM represented as a practice in the project stage is important to understand how the digital data will be used throughout the building cycle.

There have also been a number of problems identified in relying on standards, processes and procedures. While formal processes make explicit knowledge known, it is necessary for the written material to be continuously updated otherwise people will not trust it and stop using it (Javernick-Will and Levitt, 2010). The approach of Construction Operations Building Information Exchange (COBie) in gathering data incrementally throughout a project for later use for FM decisions (East, 2009) has also been criticised. Recent research have found that relying on processes such as COBie have the potential to exacerbate organizational divisions by making the transfer of information less transparent and reducing the opportunity for informal conversation such as that as ‘messy talk’ when important information is exchanged (Anderson et al., 2012, Dossick and Neff, 2011). Social methods allow for all types of knowledge to be shared (Javernick-Will and Levitt, 2010). This research addresses a gap in the literature by examining different practices that traditionally do not connect but are brought together with the aspiration of improving knowledge transfer. The following case study examines the FM representation in the delivery of London 2012 and the role the Olympic Delivery Authority (ODA), as client representative, played in delivering data for maintaining and operating the facilities. It is argued here that the client’s role of representing FM is pivotal in the project in delivering data that will be used in FM practices and enabling knowledge transfer.

# RESEARCH METHODS

The research is based on projects involved in building the venues and park in the London 2012 Games. The aim of this paper is to examine how the client facilitates FM involvement in delivering appropriate data at project completion. The case study approach provided a level of in-depth information which cannot be achieved through a general survey of large sample sizes (Yin, 2003, Eisenhardt, 1989). The ODA was a public body and a temporary organization with the goal to deliver the London 2012 games and provide a legacy to last beyond the games.

Set up in 2006 as a temporary organization to deliver the games, the ODA was project sponsor and represented the client requirements during the projects. Their delivery partner organization was a conglomerate of three organizations, CH2M Hill, Laing O’ Rourke and Mace, known as CLM. The case study is considered exceptional as the main objectives was on legacy and therefore had an inherently long term perspective for the use of the data from projects. Also this case differed from other construction/infrastructure projects as it had an immovable deadline, the venues and park needed to be delivered before the Games began in July 2012.

Negotiations to study data handover in Olympic projects started in 2010. The result of these negotiations was an examination of three projects, the Stadium, the Velodrome and the Structures Bridges and Highways as well as an examination of the programme level of these projects with data collection going from March to May 2011 with one interview occurring in August. In total, eighteen interviews were conducted with various representatives involved in the delivery of data at the end of the project. Many of the participants were from large multinational companies some coming from the oil industry and had experience in large infrastructure projects. The backgrounds of participants were either in facilities management, document control, project management or information management.

As well as conducting interviews, ODA guidance documentation formed part of the data collection and provided background material to the study and the interview questions that were asked to participants. The questions were open and were focused on the delivery of digital data at the end of the project. The participant’s involvement in the project differed, therefore their ability to answer our questions varied. Interviews lasted from fifteen minutes to one hour and a half. The interviews were transcribed and were imported into a qualitative software coding program. Codification of data involved an overarching code called ‘handover of data’ and further categories of codes that were codified within the overarching code. For this study the focus was on the codes of 'operational time line' and 'project time line' as it is not possible to examine the entire amount of data. By focusing on these codes, a close examination on how the client connects the project to FM practices was conducted. The codes were further narrowed by tabulating each of these codes and recoding to include "client as point of focus", "working within limitations" and "thinking of end user". A narrative was then written over a number of codes that were overlapping in themes. The following findings are a result of this analytical approach.

## FINDINGS

The findings are sectioned into the client approaches that were identified for the knowledge transfer of data from projects to facilities management. Quotations from project participants are in italics and are used to support the evidence that is being presented.

### Creating a culture for knowledge transfer

Creating a culture for knowledge transfer from projects into FM in the Olympic projects goes back to the theme of legacy which was translated in project aspirations. The role of the ODA, as project sponsor was to represent the client's requirements within these aspirations. The ODA was forward thinking by encouraging a perspective that the project is 'part of the story' with a much broader story that would continue as a legacy of the project data and records.

> *So because we're a public body we're much more careful about needing to produce the record and very conscious of the fact that we're only part of the story and the legacy company take on this and we're only part of the way through the story. We need to make sure that that data is provided to others to finish it. We're very conscious of the need to have accurate records so they're then passed over to the successors.*

The identity of the ODA as a 'public body' influenced the need to produce public records. However, this need was underlined with the ODA being forward thinking and conscious of the legacy theme through considering the successors of the projects. The vision of the ODA was for the long term value of the buildings and the infrastructure that was coming out of the Olympic projects. The aim of delivering accurate records for FM at the end of the project was to ensure the legacy of data from the project would live on in the operation and maintenance in the as-built facilities.

### Strategic knowledge transfer to FM

The ODA faced the challenge of building requirements for a diverse number of owners across the park that were known and unknown. For example, the decision for public ownership of the Stadium happened in August 2012, while it was known that the Velodrome would be owned by Lee Valley Regional Park Authority well before its completion in 2011. Guides and processes for meeting data handover requirements aided in managing this challenge.

Guides and processes were developed from NEC 3 http://www.neccontract.com/about/index.asp . This covered the deliverables for Pre-completion; Testing and Commissioning; as-built documentation; Build energy log books; Operation and Maintenance (O&M) Manuals; Health and Safety (H&S) files and Consents and Licences. These guides facilitated in relaying to contractors what the ODA, as client representative, wanted in the data deliverables for future FM decisions. Different standards such as Building Services Research and Information

Association (BSRIA) Class D https://www.bsria.co.uk/ were met in developing the O&M manuals while Construction Design Maintenance (CDM) regulations were used for H&S files. However, there were criticisms that these standards and the bodies who regulate them do not talk to each other and do not fully understand the outcomes of the data delivery into FM.

> *One thing I notice in the industry is that there are lots of bodies out there that….BSRIA will deal with O&Ms, CDMs will deal with Health & Safety. No one has actually succeeded in trying to bring all of that together in some sort of cohesive logical format. So you talk to people in BSRIA, they don't really understand elements of the construction testing, commissioning and how all of this kind of starts, so there never seems to be a DNA of these projects to start with. So you have very good practices and processes and bodies out there but I am in the facilities management world so I kind of….I see the aftermath of dealing with poor documentation.*

Logical formation of processes for the delivery of data that encompass standards that are required to be met is important. However, the above points out that the bodies who regulate and produce standards and processes are individually good but when they are put alongside other standards, results in illogical data delivery that do not translate into the FM 'world' where the above interviewee implies, poor documentation is delivered. If the bodies behind these standards and regulations collaborated, there is an implication that logical data could be delivered into FM. However, the main benefit of these guides and processes in the Olympic projects was that they laid out the requirements of what the client wants delivered. The ODA attempted to move beyond what is required to be delivered and also considered how the data would be used in FM by involving them early in the project.

**Knowledge transfer through social interaction**

There were FM connections between some of the projects and FM through the construction contracted companies. The company who was contracted for constructing the Velodrome received the contract to maintain the facilities. Having the same company involved in the project and takeover the maintenance contract was perceived as an advantage for knowledge transfer though the people taking care of the FM services are unlikely to have been involved in the building of the structure.

> *… and the overall strategy that has been adopted is as far as possible, we've looked for our construction contractors to then take on the FM responsibility so in the example of the Velodrome the building contractor is now separately contracted to provide the FM services… so that had some benefit in terms of the knowledge transfer that's actually we were keeping it with, now it maybe they are different parts of the organization so if you look at the Velodrome the key part for the FM is the building services…the contractor is the same contractor… but the people would have been very different so we've not suddenly got somebody who worked on the job but we have got somebody within their FM team so at least there is knowledge transfer within the company.*

The above implies that the ODA was thinking of the data as a continuation of the project by involving the same companies to take up the FM contract. There was an assumption that knowledge would be transferred easily within this company even though it was unlikely that the same people who were involved in the project would be involved in the FM contract.

There was direct FM involvement within projects through a social interaction for the transfer of knowledge. One example of this was a 4 week to 6 month transition period. The transition period proved valuable for these FM teams as it provided an opportunity to start to understand the data they were receiving as the project came to a close. It was seen as a period that the FM teams could mobilise themselves to use the data and plan how they would manage the facility they were receiving.

> *It's interesting, because what tends to happen in the industry is you build it, you finish it and you hand it over to someone to manage and there is very little transition. With a pullback transition 3-6 months before completion so that the FM teams are getting themselves fully mobilised so at the point of completion of that asset they know what they have got and they know how they are going to manage it.*

The involvement of FM early and the 'transition' period opens up the possibility for not only explicit knowledge to be transferred by data repositories but the transfer of knowledge through social interaction with those who are creating it. The FM end users have the opportunity to understand at an early point what they are receiving and think about how to mobilise this data within their own processes and systems.

**Knowledge transfer through representation of FM practice**

As well as considering who will take over the data after project completion and attempting to involve FM end users early when the FM contract was known, the ODA also had an FM representative within its project team. The Velodrome, for example, had an FM representative from the ODA since 2008 which was three years before handover.

> *My prominent role is in FM planning and delivery. So in terms of data, we review the quality of the information coming across from construction, so O & M manuals, building log books, information of that type. We set guidance for what should be included and set guidance on how it should be provided and then obviously review the quality of it when it comes through, with a view to our maintenance teams then using it moving forward post-completion; so into operations through the games.*

The review of information was conducted during the project, thus ensuring what was required would be delivered as well as reviewing the quality of that information. The use of information was also considered at this stage which is important as it moves beyond the check-list of requirements in terms of 'what' is being delivered into thinking about 'how' FM practices will use the information. The deliverables of FM listed in our conversation with this ODA FM representative were that of documentation, e.g. Operational and maintenance manuals that can also just as easily be delivered through paper rather than within the software system that it was delivered within. Indeed, the owner of one facility after project completion referred to the strong use of paper within their FM practices.

> *As an operator, I think it's still the case that, frankly, we're not saying that we only utilise paper systems but actually, as an operator, that usually is the simplest way in actual fact. To just simplify things down to one side of A4, you might use that on a computer screen rather than an actual piece of paper but simple systems are what you need to operate. You can end up with huge documents, huge files of which you only use one line or something like that, you can't function like that.*

In this context, this owner did not see the difference in data being presented digitally as opposed to that produced through paper. The data was a means to the decisions in operations and the preference for presenting the data was through simple practices. A representation of this simple practice was through paper. There is an implication that knowledge is not transferred fully into the FM practice as there is a perception that the data from the project is complex and what is needed is more simple data.

**Summary of findings**

The ODA used a number of approaches that enabled the involvement of FM in data handover. There were enablers that facilitated the knowledge transfer through FM involvement. There were also disablers that limited the amount of knowledge transfer which was particularly noted as the project came to an end. Table 1 outlines the specific approaches and the enablers and disablers.

Table 1 Approaches for knowledge transfer through FM involvement

| **Approach** | **Enabler** | **Disabler** |
|---|---|---|
| Creating a culture | Forward thinking client<br>Legacy theme | No control over culture after data handover |
| Strategic | Guides and processes | Disconnected regulators of standards |
| Social interaction | FM connections to the project | No project connections to FM |
| FM representation | An FM representative with understanding of how data would be used after data handover | No continuation of FM representative after data handover |

The ODA represented the client during the project and created a culture that thought beyond the project enabled by being forward thinking and the theme of legacy that run throughout the London 2012 games. The limitations of being a client representative up until data handover meant that it had no control over the data once it is received by the legacy owner. The strategic approach was enabled through guides and processes that were underpinned by industry standards. However, there are disconnections between the industry standards that impact on the data that is received by FM as it can appear illogical. Social interactions enabled FM connections to the project which is positive in preparing them for use of the data after handover. However, these social interactions seem to be one way as there are limited connections to the project after the owner has received the data. This relates to the last approach in having FM representation during the project which enabled an understanding of how the data would be used after handover. However, this FM representative also completed his role once the project was complete and there was no continuation of this role after data handover. The main theme coming out from these findings is a lack of continuation of these approaches to knowledge transfer once a project is complete.

## DISCUSSION

The approach that the ODA used in projects is a move toward viewing facilities management, not as the next stage but part of the process in delivering data that can live beyond the project. The project data was being developed with a future purpose for facilities management which was enabled by the culture and strategy within the project. The ODA was a 'visionary client' (Becerik-Gerber et al., 2012) developing a culture of legacy which was a theme that ran through all aspects of London 2012 and was noticeable for data handover into facilities management. Guides and processes set an explicit strategy for data handover and were useful in enabling contractors to understand what the ODA, as client representative, wanted to be delivered. However, the bodies for which these processes are developed were criticised for not collaborating which results in an illogical format for data delivery that facilities managers have to synthesise. Involving the end user, such as that of FM would facilitate knowledge transfer giving a further understanding of the outcome of these requirements. BIM execution plans do call for the involvement of FM for data delivery (GSA, 2011, Messner et al., 2012) and the ODA did involve FM in an attempt to ensure the transfer of 'useful knowledge' (Brown and Duguid, 2001). However, linkages were one way and while it is useful to involve the end user in developing knowledge transfer, it may also be useful to involve the creators of that knowledge for integration in its new context.

Brown and Duguid (2001) refer to 'useful knowledge' in terms of involving practices that are to use the knowledge they are receiving as different practices have different perspectives of what useful knowledge is. The ODA attempted to create useful knowledge by involving FM through social interaction which is necessary for knowledge transfer (Anderson et al., 2012, Javernick-Will and Levitt, 2010). There was an FM representative within the ODA team as well as incidences where FM personnel were involved in a 4 week to 6 month 'transition period'. Thus going beyond passive "checklists" (Whyte et al., Forthcoming) in data handover approaches and creating social knowledge transfer. In order to maintain links with the project, the ODA sometimes contracted the same construction company to take up the FM contract. However, it cannot be assumed that knowledge transfer is done between different practices within the same company as the literature indicates that practices are likely to identify with their own practices for knowledge transfer rather than within their own organization (Brown and Duguid, 2001). There was a move away of relying on the passiveness of outlining requirements within documentation and creating a social knowledge transfer from project to facilities management.

Involving FM at an early stage allowed FM to have visibility in the project and aided project teams to think of the data for beyond the project. However, the role of the ODA as a visionary client ends once the data is handed over and there is no control over the vision of data legacy once the data is taken over by the new owner. The example of one owner, referred to how the data systems that are handed over from the ODA are viewed as complex and the FM practices of this owner are primarily paper based. This problem has also been referred to in relation to BIM where the FM practices of paper usage is not considered (Anderson et al., 2012). There are efforts to get intuitive data across to FM in the project but these efforts are wasted if the data is not being used to its potential. In the literature there are many areas of outlining how intuitive data promoted through BIM can support FM services (Becerik-Gerber et al., 2012) but actual take up of this type of data is quite dependent on the type of FM organization (Bainbridge and Finch, 2009). The above case highlights the enablers and disablers of knowledge transfer from project to FM and a need for continuous representation that links across both contexts.

## Conclusion

The case study was unique as the Olympic projects were one off and the time-scales were immovable so there was no flexibility in going beyond deadlines. However, the lessons learnt from the Olympic projects are applicable to other projects in terms of the approaches in thinking about the use of data across the life-cycle. The ODA, as client representative, had a clear vision of legacy and this filtered through for data handover. The contribution of this paper to the literature is examining knowledge transfer from practices in the project and FM that traditionally do not connect and seeing this as being facilitated through the client. The client facilitated the involvement of FM in data handover through; 1) creating a culture for knowledge transfer in the project; 2) strategic knowledge transfer through guides and processes; 3) social knowledge transfer through making connections with FM end users to the project; 4) knowledge transfer through FM representations. While involving FM was enabled by these approaches, there were also disablers that could potentially limit the amount of knowledge being transferred which were primarily based on not having a continual representative between project and FM to facilitate integration of the data that is handed over into FM.

Knowing who the owner of the data after project completion is an advantage in deciding what data and formats will be used as well as opening up the possibilities of having FM involved at the earlier project stages such as the design stage. Having FM involved in the development and in a transition period was extremely important in ascertaining how data is used in FM. However, even earlier involvement of FM, at the requirements stage may result in a further understanding of the use of what FM receive at the end of the project. On the other end of the scale, FM may also need incentives or a role similarly to the ‘visionary client’ where participants from the project can assist in knowledge transfer of the data after handover.

The study is limited to focusing on involving FM for handover projects close to completion. Further research is needed to understand how FM teams synthesise the data into their own systems after data handover and how FM knowledge should not start from late stages but from early stages of a project.

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# DEVELOPING STANDARDS TO ASSESS THE QUALITY OF BIM CRITERIA FOR FACILITIES MANAGEMENT

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## ABSTRACT

With increasing frequency in the use of BIM for facility handover, organizations have to address the quality of information. Previous studies have shown the substantial impact inadequate interoperability of information has on facility operations. Since 2009, the Pennsylvania State University (PSU) has implemented Building Information Modeling (BIM) on all new projects over $5 million and major facility renovations. The BIM criterion was developed by determining facility geometry and data level of detail required to perform typical operations tasks. The success of operations also depends on the completeness and accuracy of the information received. Therefore, PSU has developed a standard process to audit model information during the lifecycle of the facility project.

This paper will discuss the procedure developed by PSU to plan the validity and reliability of the model geometry and information. This includes an overview of risk forecasting and analysis procedures created as a rule set for data review, as well as highlight quality grading scales used for model acceptance. Additionally, one case study will be reviewed, depicting the developed quality control standards for both a new construction project and a major renovation. The Pennsylvania State University has ten projects implementing BIM that will be delivered over the next two years and the quality of the information received is essential to the success of operations and maintenance of these facilities.

**Keywords:** Building Information Modeling; Facilities Management; Model Auditing; Quality Control

## INTRODUCTION

The Architecture, Engineering and Construction (AEC) industry recently adopted Building Information Modeling (BIM) as a standard construction practice for facility projects. In order for successful execution, project stakeholders must develop and manage the exchange of information between different tasks during all phases of the project lifecycle. BIM implementation varies significantly from project to project, and so the project team must effectively design an execution strategy by understanding the goals and capabilities of all stakeholders.

Owner organizations are only beginning to outline their BIM implementation strategy for the design and construction process, as well into facility operations. In order to effectively plan for the integration of BIM into their facility management processes, a facility owner must develop their information requirements from a set of core values which align with best practices of their organization (CIC, 2012). Currently, there is no standard methodology to assess and develop owner requirements within the AEC industry. Each facility owner will have a unique data set and must look internally within their organization to understand their operating systems, identify best practices, define their essential information needs, and then contractually obligate project teams to deliver these requirements at different phases during the project lifecycle.

To achieve maximum benefit from project BIM implementation, all project stakeholders must collaboratively develop a strategy which allows for streamlined information exchanges. This can ultimately be achieved by encouraging continuous owner input and participation.

**The Pennsylvania State University**

As owner, designer, and construction manager, the Office of Physical Plant (OPP) at the Pennsylvania State University (PSU) has been successful with accelerating BIM technology in both new construction projects and facility operations. The OPP currently requires the use of BIM on all projects valuing over $5 million and any other major facility renovation. Using the recommended processes and templates from the BIM Project Execution Planning Guide, the OPP has developed an effective BIM implementation strategy for project stakeholders to collaborate during all phases of a facility project (CIC, 2009). For the purpose of this research, the researchers focused on the development of a procedure to streamline the information exchanges between outside consultants and several departments within the OPP.

## MODEL AUDITING RESEARCH METHODOLOGY

The focal point of this research is to develop a standard procedure for the verification of the completeness and accuracy of modeled facility information. When documenting the research findings, the first step was to review and compare any ongoing projects with a similar approach. Next, the facility information requirements were determined along with the priority of each attribute. Finally, a case study was used to validate the required facility information and document the appropriate method for auditing the accuracy and completeness of the asset data. The following detailed research steps were conducted to develop the concepts addressed in this paper:

1. Interviews were conducted with various institutional owners collecting building information throughout the US to determine the initial value of the research.

2. Relevant literature was reviewed to document previous studies as well as ongoing quality control initiatives.
3. Standard facility information requirements for PSU projects were documented using previous completed work by the Virtual Facilities Group.
4. Key members of the OPP were interviewed to prioritize the required facility information for future use in operations.
5. An initial model auditing process was developed to qualify facility information and geometry on new and major renovation projects.
6. The developed model auditing procedure was then tested on a large dormitory project on a PSU campus.

The case study results were gathered during meetings with the project stakeholders. A research team member attended each of the following meetings to integrate facility information into the BIM Model: BIM Execution Planning kick-off meeting, Pre-Coordination meeting, and 3D Coordination meetings. In addition to meetings, the project engineer responsible for BIM implementation was helpful in collecting data on the project. This structure was used to determine the attribute requirements for each maintained asset considered critical in the case study project.

## QUALITY MANAGEMENT FOR DOCUMENT TURNOVER

Efforts to manage, assure, and assess the quality of information at facility handover have been ongoing since the adoption of BIM as a project tool. A significant number of case studies from the past have documented the use of 3D Laser Technology and other tools to help capture as-built facility information for operations (Woo et al, 2010). While these have been effective in the capture of spatial and geometric data, there have been few examples of owner organizations capturing and handing over information seamlessly for daily maintenance and operations. With increased reliance on the automated delivery of digital data for operations, the industry has been pushing towards the use of applications that would allow the verification of the accuracy of facility information. Solibri model checkers are commonly implemented on projects with a purpose for automated code compliance verification. Compliance to specified standards and model integrity are verified using vendor based applications, as are spatial programs for zoning and circulation for design validation.

For effective implementation, these automated tools require a standard set of rule set for comparison. The purpose of these tools is to verify the accuracy of information for a particular use case. To effectively develop these rule sets, owner organizations will have to begin with an understanding of the purpose of requiring accurate information and the need for managing its quality for operational uses.

### Value of Information for Facilities Management

Facilities Management (FM) ensures that the built environment performs the functions for which the facility was designed and constructed. The overarching goal of this service is to improve equipment effectiveness, return equipment to proper functioning conditions, control Life-Cycle cost and provide a safe and functional system for its occupants (WBDG, 2011) (NASA, 2008).

BIM is increasingly recognized as one of the ways of handing over accurate information that would be of value (Jordani, 2010). The accuracy of this information assists in the decision making process to properly maintain and operate a facility. Reliable and optimized decisions for operations can be made using known and accurate data (Whyte et. al, 2010). Apart from the accuracy and completeness of facility data, owner and operator knowledge of information management is another ongoing challenge. A method to develop an understanding of the required information for operations and optimizing this information would benefit a team with developing ground rules for the auditing procedure.

**Data & Process Standardization: Challenges**

The Construction Operations Building Information Exchange (COBie), developed by the United States Army Corps of Engineers was one of the first documented information capturing mechanism for facilities data. This industry open standard for delivering information from construction to operations provides an opportunity to capture and handover complete and accurate information. Organizations developing their own requirements for their facility information must specify a proprietary format for the capturing and delivering of the information (CIC, 2012). In either of these cases, best value is achieved when the required information for operations and maintenance is obtained and delivered at the required time and of the desired quality.

As efforts to standardize data and processes move forward, process challenges must be understood by the entire project team in order to achieve maximum results. From the surveys and interviews that were conducted as part of this study, one of the biggest challenges for industry implementation is the current level of understanding and knowledge of the end users, the same users who require and use the information for operations. Some of the other challenges mentioned to the standardization, improvement and betterment of quality were: lack of adequate quality assurance and control mechanisms; inadequate definition of responsibilities for information handover; incomplete definition of deliverables or requirements and lack of a tested process to ensure desired handover of information from design and construction to operations. The purpose of this survey was to understand the challenges with the information handover and address possible methods to address these issues.

## DEVELOPING OWNER LEVEL OF DETAIL REQUIREMENTS

Project teams must not only consider the information requirements for the project, but also recognize their responsibility for providing the owner with much of the operational data required to maintain a facility. However, few owners have defined these needs and how this information can be effectively integrated into their facility management systems. An owner organization must develop an understanding of their operating systems and procedures to identify where project information can add value to their daily operational tasks, recognize areas of improvement within their current processes, and then develop their facility information requirements (Kasprzak et al. 2011).

In order to develop a comprehensive data set, the owner organization must address the following: what information is considered essential and high priority to their operations processes; when and by whom should this information be developed during the project lifecycle; and what are the contractual and legal concerns associated with the development of this information. Other considerations include who is responsible for auditing and maintaining the data and what systems will be used to manage the acquired data throughout the lifetime of the facility (Fallon et all, 2007). After performing this assessment, the owner organization should explicitly request the facility information requirements as part of the contracted project deliverables. With this knowledge evident during project onset, the project stakeholders can develop an effective information exchange strategy to streamline and validate information exchange processes between the facility lifecycle and facility operations.

**OPP Development of Standards**

After participating as an owner representative for several projects implementing BIM on the PSU University Park campus, OPP recognized a need to further develop their contract language to include owner data requirements. Concurrently with an initiative to upgrade their existing facility management system, OPP began an assessment of internal operations processes cross departmentally and identified where additional information captured during the project lifecycle to add value to the existing workflows. Ultimately, the goal was to develop a data exchange solution to eliminate the duplication of effort and information that seemed to be occurring when multiple parties were accessing this information.

The established owner requirements document contains the facility asset requirements for all campus projects implementing BIM at PSU. At a minimum, each asset is to include a listed set of parameters, a barcode, O&M manual, installation guide, submittal information, warranty documentation, and commissioning report. It is the responsibility of the appropriate project stakeholder to provide and verify design, construction, or commissioning information to meet the deliverable standards for the project. Per the developed contract language, these information sets must be provided to PSU at different points during the project lifecycle to audit and validate content.

## PLANNING THE MODEL AUDIT PROCEDURES

Facilities Management services, for both public and private organizations have employed either directly or a version of the following maintenance programs: Preventive Maintenance, Condition-Based Monitoring and/or Reliability-Centered Maintenance (NASA, 2008). The goal of these maintenance programs, as they evolved, was to mitigate the risk of occupation and use of facilities in the case of equipment, system or facility function failure. With the FM industry focusing on reducing the risk of occupancy, the quality planning procedure adopts risk analysis as the root of the method.

**Risk Analysis for Informed Decision Making**

Risk analysis (risk assessment) has been adopted across a wide number of industries for the benefit of reducing unforeseen risks or mitigating their impact. The construction industry has used risk assessment for managing risks on international projects to improve project performance (cost, schedule and scope) (IPRA, 2003). The facilities maintenance industry has used risk analysis to make informed maintenance and operations decisions and prioritize maintenance activities (Backlund and Hannu, 2002).

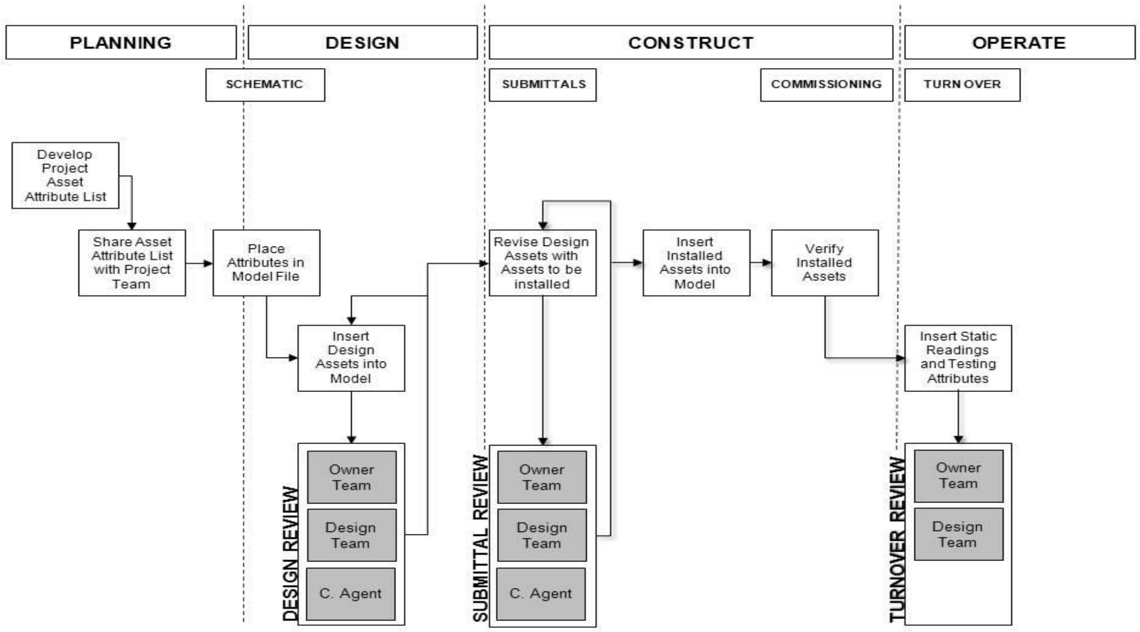


Figure 1: Model auditing process for a typical Penn State project

The risk analysis procedure has a number of variations that exist to cater to the specific needs of a project, technology or end user. However, it is important to understand that the procedure intends to help plan and make decisions based on: potential hazards or risks, risk frequencies, and risk impacts. To assist with the planning and decision making for developing the model and information auditing procedure, these issues were modified to address the needs of facilities management, operations and maintenance:

- What facility information is required for regular and reliable operations of a facility?
- How do facility elements relate to one another? (based on hierarchy, naming, tracking, etc)
- What systems and components pose the biggest threat in a facility? (in terms of cost, frequency of failure, time and expertise required for maintenance)
- What information for these prioritized system and components is required for the reliable maintenance and to reduce risk?

The risk analysis approach could be either qualitative or quantitative, with the former basing decisions off of experience and know how, and the latter on recorded information and numbers. The choice of the method to be adopted will ideally be based on the availability of information and the experience of the facility owner's team implementing the procedure. At PSU, a qualitative approach to risk analysis was adopted while developing and documenting the initial model auditing procedure. From an initial run of the procedure at OPP, the steps required for the planning of the model auditing procedure that was documented for further validation are:

1. Determine and document facility information required for operations
2. Identify the relationship between different elements of the facility
3. Classify information based on task or use case for facility operations, as seen in Table 1.
4. Prioritize information using the risk analysis procedure- qualitative or quantitative, as seen in Figure 2.
5. Identify and require responsibilities for model and information auditing on projects

| **Risk Level** | **Definition** |
|---|---|
| **High** | Information cannot be accepted until it has undergone a rigorous quality management process to verify and validate the information |
| **Medium** | Information can be accepted before validation through a quality management program, but has to be observed and resolved as its use progresses through operations. |
| **Low** | Information can be accepted before validation through a quality management program, but has to be observed as services progress through operations. |

Table 1. Information risk classes and definitions

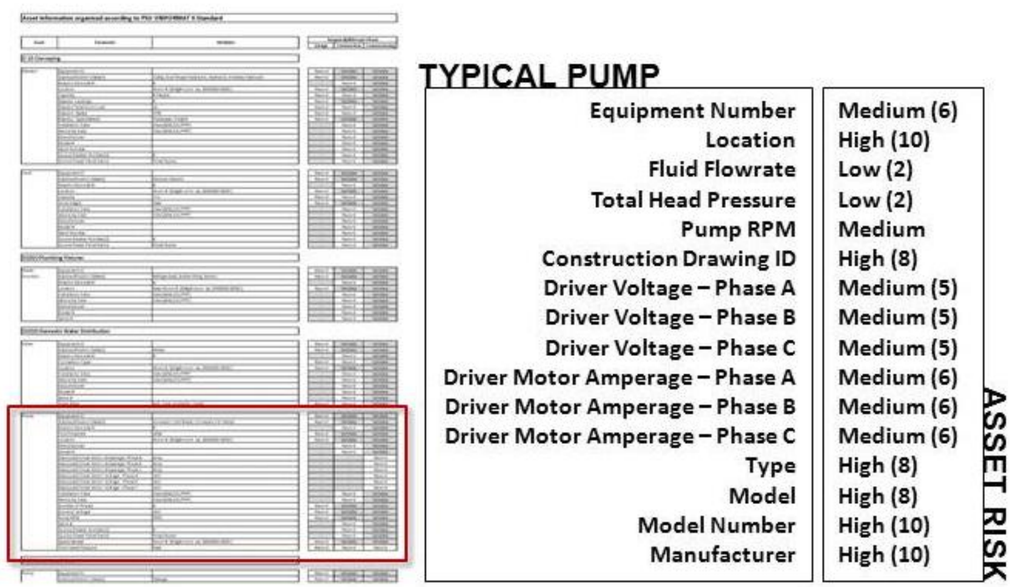


Figure 2: Asset attributes for a typical pump including level of risk for each

These are an initial set of steps that would be required to plan the model and information auditing procedures for an owner organization. This process will be further validated and documented on other projects for continuous improvement.

## MODEL AUDITING CASE STUDY

In order to test the developed model auditing process, OPP chose the South Halls Complex project at University Park, PA. Totaling $94.1 million, this project, shown in Figure 1, will be completed in four phases. This project includes significant facility renovations to the four existing duplex residence hall buildings and dining commons, as well as the addition of a new residence hall. The major facility infrastructure upgrades will include new energy-efficient systems, new roofs, private bathroom clusters, and suites that include a kitchenette, dining, and lounge areas. The new residence hall, incorporated into the overall plan will add 45,000 square feet in four above-ground floors and house 211 beds in 108 rooms.

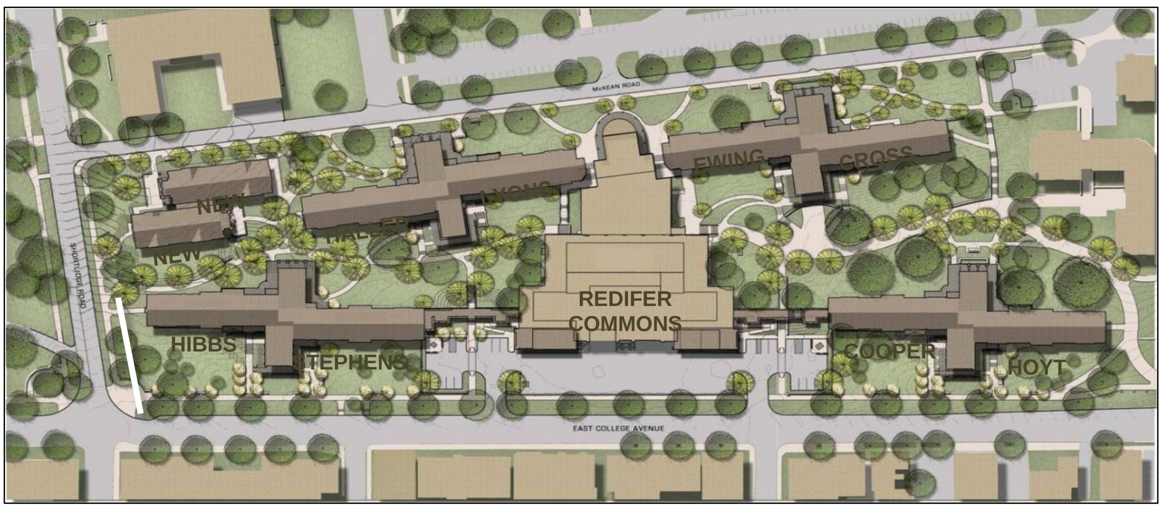


Figure 3: Validation Case Study- South Halls Complex Project, Penn State University, University Park, PA. Image courtesy of Barton Malow.

### Initial Findings and Challenges

The OPP was able to establish a functional information hierarchy for campus facility projects based on the level of risk it imposes on current operation processes, as shown in Figure 2. Generally, a facility contains spaces which are served by systems. These systems are comprised of different components and assets which have a location. A particular asset may assist one system and serve many spaces. The OPP uses both a functional and system based hierarchy within their current facilities management systems; thus, location data is considered high priority information and is even standardized within the naming convention of the assets.

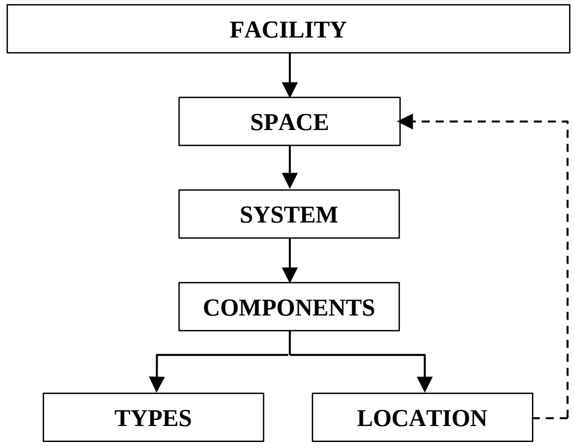


Figure 4: OPP facility element hierarchy

An important lesson learned during the initial implementation and development of the procedure was the way information had to be assessed and categorized. While developing the strategy to implement and contractually require model auditing, it was understood that information had to be managed on a use or facility maintenance task basis, as shown in Table 1. The following departments were involved with the validation of the facility information: Virtual Facilities Group (VFG), Work Control Center (WCC), Facility Resource and Planning (FIS), Energy and Engineering Group (EE), and Building Automation Group (BAS). This helps identify the responsible parties for auditing and approving the set of information tracked to maintain the facility.

| Mark | Barcode Number | Model | Manuf. | Serial Number | Space: Level | Space: Name | Space: Number | FCU Cooling Capacity | FCU Heating Capacity | Equip. Type | BAS Control? | BAS Identifier |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| FCU-7 | 28127 | CXB06 | IECINT.L ENVIR | 005690-4565 | HALLER GROUND FLOOR | MAINT. SHOP | H012 | 0.0 Bty/hr | 0.0 Bty/hr | 2-PIPE | NO | --- |
| FCU-6 | 28128 | CPY02 | IECINT.L ENVIR | 0096845-6254 | HALLER GROUND FLOOR | OFFICE | H006 | 0.0 Bty.hr | 0.0 Bty.hr | 4-PIPE | YES | FCU004 |
| VFG | | WCC | | | FIS | | | EE | | | BAS | |

Table 2: This is an example of the OPP Task Based Information List.

## FUTURE WORK

After seeing the initial results of the case study, the OPP is planning to require these information deliverables on all campus facility projects, not just those implementing BIM. This effort will require another revision to the existing contract language and evaluation of information exchange processes for projects under $5 million, as well as facility construction projects developed internally in the Design Services department. The OPP will also continue to develop an integrated BIM to FM data exchange solution in order to improve and automate information exchange processes. While experience and technological capabilities may vary between specific owner organizations, developing thorough owner requirements is necessary for creating a more effective facility design and operations workflows during the lifetime of a facility. The model auditing process should also be tested with an inexperienced owner to thoroughly validate the developed procedure.

In regards to the risk analysis procedure, an investigation needs to be performed to identify the different effects of the choice of the approach (qualitative versus quantitative) on analysis results. However, a quantitative approach would be more challenging to implement if an owner has yet to establish a formal facilities management program that maintains a record of facility operations.

## CONCLUSIONS

Prior to the development of this procedure, facility information was typically handled by project teams with little regard to its use in facility operations. This model auditing procedure revised this process and has developed a task or user based approach to the creation and validation of the project data sets. This method is an alternative approach to planning quality assurance and control procedures, minimizing risk while adding value when using facility information during operation processes. This project's outcome will, in time, continue to support the effort to implement improved operational strategies and begin to streamline facility information across all OPP departments at the University Park campus. The information exchange procedures implemented by the Office of Physical Plant at The Pennsylvania State University represent an excellent opportunity to identify and develop best practices solutions for facility delivery and facility operations within the AEC and FM Industries.

## ACKNOWLEDGEMENTS

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# A CASE STUDY ON IMPLEMENTATION OF THE BIM PLANNING PROCEDURES FOR FACILITY OWNERS

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## ABSTRACT

Many facility owners are beginning to adopt Building Information Modeling (BIM) to effectively operate and maintain the facility. The BIM Planning Guide for Facility Owners helps in planning and integrating BIM throughout the organization and the life cycle of the facility. To assist owners with planning for the adoption of BIM, three procedures were developed. These procedures include BIM organizational strategic planning, BIM organizational execution planning, and BIM project procurement planning. These procedures were developed through content analysis of available industry and research documents; industry interviews; workshops; and observational case studies. As part of the validation for the procedures developed, case studies were conducted in which the procedures were implemented.

To understand the effectiveness of the procedures outlined in the BIM Planning Guide for Facility Owners, a case study of a well-established real estate development firm was conducted. The case study was conducted by implementing the strategic planning and procurement planning procedures that are applicable to the organization's needs. Within the strategic planning procedure, the organization assessed their needs, targeted goals, objectives, and uses, and developed a plan for implementation. The procurement planning effort focused on developing the contract language necessary to accomplish the goals and objectives. The lessons learned from the case study will help in future planning and implementation along with the overall improvement of the procedure.

**Keywords:** Building Information Modeling, Owners Guide, Procurement Planning, Strategic Planning, and Validation.

## INTRODUCTION

As defined by the U.S. National Building Information Modeling Standard (buildingSMART alliance 2007) Building Information Modeling (BIM) is defined as “The act of creating an electronic model of a facility for the purpose of visualization, engineering analysis, conflict analysis, code criteria checking, cost engineering, as-built product, budgeting and many other purposes.” Construction owner organizations have started adopting BIM within their processes and are gaining benefits from improved design and construction of projects. Some benefits of BIM for owners are better communication, lower project costs, avoiding rework, better project outcomes, and better performing buildings (Young et al. 2009). BIM is not just limited to the design and construction process but it can be used to support the lifecycle of a facility. Owners can benefit from this process. Model information can be used for operations and maintenance of a facility and it can support any future renovation activity by providing all the necessary information about the facility (Computer Integrated Construction Research Program 2012).

The Computer Integrated Construction Research Program at The Pennsylvania State University has developed a BIM planning guide for facility owners hoping to help owners realize the benefits of BIM throughout the entire facility lifecycle. BIM planning procedure for owner organizations can be done in four stages – developing BIM Organizational Strategic Plan, developing BIM Organizational Execution Plan, developing Owners BIM Project Procurement Plan, and developing a BIM Project Execution Plan Template.

This paper documents the procedure and results of a case study on the implementation of BIM planning procedures for facility owners. The procedure presented in the BIM Planning Guide for Facility Owners (Computer Integrated Construction Research Program 2012) should be adapted based on the organization’s requirements. Strategic plan and procurement plan were developed after studying the requirements of a real estate development company (located in the USA), which is interested in implementing BIM planning for their company. The company has offices in different regions throughout the country but the case study was conducted on just one regional office which has completed over 17 million square feet of projects. The case study helped in understanding that there is no single success formula that suits every organization. Every organization has a different structure and the BIM implementation plan should be tailored accordingly. Along with the implementation procedure, this paper also presents the important lessons learned from the case study which will be helpful for owners interested in implementing BIM within their organization.

## BIM STRATEGIC PLANNING PROCEDURE

An organization should generate a BIM strategic plan to begin implementing and integrating BIM within their organization. As defined by John M. Bryson (2011), "Strategic planning is a disciplined effort to produce fundamental decisions and actions that shape and guide what an organization (or other entity) is, what it does, and why it does it."

Strategic planning helps an organization to achieve the goals and help focus on the mission and vision of it. The internal capability of an organization and its performance with respect to the external competition improves with the help of a strategic plan. To plan BIM at a strategic level, an owner organization should follow the three steps of the BIM Strategic Planning Procedure (Computer Integrated Construction Research Program 2012). These steps include: assessing the organization's internal and external BIM status, aligning the organization's BIM objectives by identifying the desired level of maturity, and the BIM maturity level through developing a defined advancement strategy. Assessing the organization determines the areas of focus for future BIM implementation. Establishing a desired level of implementation determines the degree to which the organization will implement BIM. Developing an advancement strategy defines the transition process for the integration of BIM into organizational business practices. A roadmap which displays the integration of strategic changes in a business process should be developed. It will benefit the organization by communicating the key components of the strategic plan in a simple graphical representation. The roadmap includes planning elements, time frame, current status of the organization with respect to BIM and the goal they want to reach, milestones to be achieved in the process and the BIM uses that will be used internally within the organization (Phaal, Farrukh, and Probert 2001). All the strategic planning should then be documented so that it can be used for benchmarking and measuring the performance at various points along the implementation timeline.

## BIM PROJECT PROCUREMENT PLANNING

It is important that the owner develop a clear procurement strategy including BIM contract language after generating a strategic plan. The BIM needs for a project should be determined to successfully procure BIM services on a project. When preparing BIM procurement documentation the owner should focus on areas such as team selection, contract procurement and execution requirements. Four items should be addressed within these three areas including: Request for Qualifications

(RFQ), Request for Proposals (RFP), Contract Requirements, and Standard BIM Project Execution Plan Template (Computer Integrated Construction Research Program 2012).

## CASE STUDY METHODOLOGY

The methods used to conduct the case study included collecting background knowledge of the organization, leading focus group meetings, conducting interviews with the principal personnel, and performing artifact analysis of planning and contract documents.

### Kick-Off Meeting

The kick-off meeting was conducted in the Computer Integrated Construction (CIC) research lab along with CIC team members and principal personnel of the organization. The important business drivers to be considered when investing in BIM were discussed. The cost of implementing BIM within the organization was discussed so that the key personnel can prepare a rough estimate and send it for the approval of higher authorities in their organization. The CIC team outlined the important elements which should be included in a Business Case. A Business Case is necessary to gain support for and to justify the investment in BIM. It is a multi-purpose document that generates the support, participation and leadership commitment required to transform an idea into reality. Overall, the meeting helped to understand how the organization operated.

### In Preparation for Strategic BIM Planning

The second meeting was scheduled one month after the Kick-off meeting. The organization assessed and determined areas of focus for future BIM implementation during the one month period. The CIC team emailed the BIM organizational assessment templates to the organization a few weeks before scheduling the second meeting at their office. The templates can be found in BIM Planning Guide for Facility Owners package developed by the CIC research team (http://www.bim.psu.edu/Owner/Resources/contact_info.aspx, Computer Integrated Construction Research Program 2012). The template has all the planning elements with a brief description of each. It also shows different levels of maturity indicating the existing BIM maturity level and the desired maturity level. Each level is assigned a number which starts from 'zero' and ends with 'five.' For example if the organization indicates a zero on the template, it means that the planning element corresponding to it is non-existent. Table 2 is a snapshot of the template with the planning elements and maturity level. The planning elements are given in Table 1.

## Table 1: BIM Planning Elements

| BIM Planning Elements | |
|---|---|
| **Strategy** | Organizational Mission and Goals, BIM Vision and Objectives, Management Support, BIM Champion, BIM Planning Committee |
| **BIM Uses** | Project Uses, Operational Uses |
| **Process** | Project Processes, Organizational Processes |
| **Information** | Model Element Breakdown (MEB), Level of Development (LOD), Facility Data |
| **Infrastructure** | Software, Hardware, Physical Spaces |
| **Personnel** | Roles and Responsibilities, Organizational Hierarchy, Education, Training, Change Readiness |

## Table 2: BIM Planning Elements and Maturity Level Evaluation

| **Strategy** | the Mission, Vision, Goals, and Objectives, along with management support, BIM Champions, and BIM Planning Committee | **0 Non-Existent** | **1 Initial** | **2 Managed** | **3 Defined** | **4 Quantitatively Managed** | **5 Optimizing** | **5** | **18** |
|---|---|---|---|---|---|---|---|---|---|
| Organizational Mission and Goals | A **mission** is the fundamental purpose for existence of an organization. **Goals** are specific aims which the organization wishes to accomplish. | No Organizational Mission or Goals | Basic Organizational Mission Established | Established Basic Organizational Goals | Organization Mission which addressed purpose, services, values (at a minimum) | Goals are specific, measurable, attainable, relevant, and timely | Mission and Goals are regularly revisited, maintained and updated (as necessary) | 1 | 4 |
| BIM Vision and Objectives | A **vision** is a picture of what an organization is striving to become **Objectives** are specific tasks or steps that when accomplished move the organization toward their goals | No BIM Vision or Objectives Defined | Basic BIM Vision is Establish | Established Basic BIM Objectives | BIM Vision address mission, strategy, and culture | BIM Objectives are specific, measurable, attainable, relevant, and timely | Vision and Objectives are regularly revisited, maintained and updated (as necessary) | 1 | 4 |
| Management Support | To what level does management support the BIM Planning Process | No Management Support | Limited Support for feasibility study | Full Support for BIM Implementation with Some Resource Commitment | Full support for BIM Implementation with Appropriate Resource Commitment | Limited support for continuing efforts with a limited budget | Full Support of continuing efforts | 1 | 4 |
| BIM Champion | A BIM Champion is a person who is technically skilled and motivated to guide an organization to improve their processes by pushing adoption, managing resistance to change and ensuring implementation of BIM | No BIM Champion | BIM Champion identified but limited time committed to BIM initiative | BIM Champion with Adequate Time Commitment | Multiple BIM Champions with Each Working Group | Executive Level BIM Support Champion with limit time commitment | Executive-level BIM Champion working closely with Working Group Champion | 2 | 4 |
| BIM Planning Committee | The BIM Planning Committee is responsible for developing the BIM strategy of the organization | No BIM Planning Committee established | Small Ad-hoc Committee with only those interested in BIM | BIM Committee is formalized but not inclusive of all operating units | Multi-disciplinary BIM Planning Committee established with members from all operative units | Planning Committee includes members for all level of the organization including executives | BIM Planning Decisions are integrated with organizational Strategic Planning | 0 | 2 |
| **BIM Uses** | The specific methods of implementing BIM | **0 Non-Existent** | **1 Initial** | **2 Managed** | **3 Defined** | **4 Quantitatively Managed** | **5 Optimizing** | **1** | **4** |
| Project Uses | The specific methods of implementing BIM on projects | No BIM Uses for Projects identified | No BIM Uses for Projects identified | Minimal Owner Requirements for BIM | Extensive use of BIM with limited sharing between parties | Extensive use of BIM with sharing between parties within project phase | Open sharing of BIM Data across all parties and project phases | 1 | 3 |
| Operational Uses | The specific methods of implementing BIM | No BIM Uses for | Record (As-Built) BIM | Record BIM data | BIM data manually | BIM data is directly | BIM data maintained with | [illegible] | [illegible] |

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The BIM champion of the organization assessed the present and target level of maturity they wanted to achieve using BIM. Data in Table 3 is derived from the information in Table 2. The BIM champion went through each and every planning element and highlighted the current status which is shown in Blue color in Table 2. The desired status is the status the organization wanted to reach and is shown in Red. Thus, the current maturity level is derived by summing up all the numbers allocated to each column highlighted in blue; and the target maturity level is derived by summing up all the numbers allocated to the columns highlighted in red. For example, from Table 2 the current maturity level of the planning element "Strategy" is the sum of Organizational Mission and Goals (1) + BIM Vision and Objectives (1) + Management Support (1) + BIM Champion (2) + BIM Planning Committee (0). The sum is equal to 5. In the similar way, all the current and target values of each planning element were identified and Organizational BIM Maturity level (Table 3) was developed based on that information.

The BIM champion also documented the priorities and the goals for implementing BIM within their organization. As defined in the BIM Planning Guide for Facility Owners (Computer Integrated Construction Research Program 2012), BIM Champion is a person on the project team who plays a critical role in communication and information sharing, and someone who can easily influence the success of the project in either a positive or a negative way. They will be the responsible party for each of the project team's BIM issues and will serve as the primary BIM contact for the organization.

The BIM uses which the organization wants to use were reviewed based on how and when they want to implement them. Table 3 and Figure 1 show the summary of the assessment information.

**Table 3: Organizational BIM Maturity Level**

| Organizational BIM Assessment Profile | | | |
|---|---|---|---|
| **BIM Planning Element** | **Current Level** | **Target Level** | **Total Possible** |
| Strategy | 5 | 18 | 25 |
| BIM Uses | 1 | 4 | 10 |
| Process | 0 | 4 | 10 |
| Information | 0 | 4 | 15 |
| Infrastructure | 0 | 3 | 15 |
| Personnel | 0 | 7 | 25 |
| **Totals** | **6** | **36** | **90** |

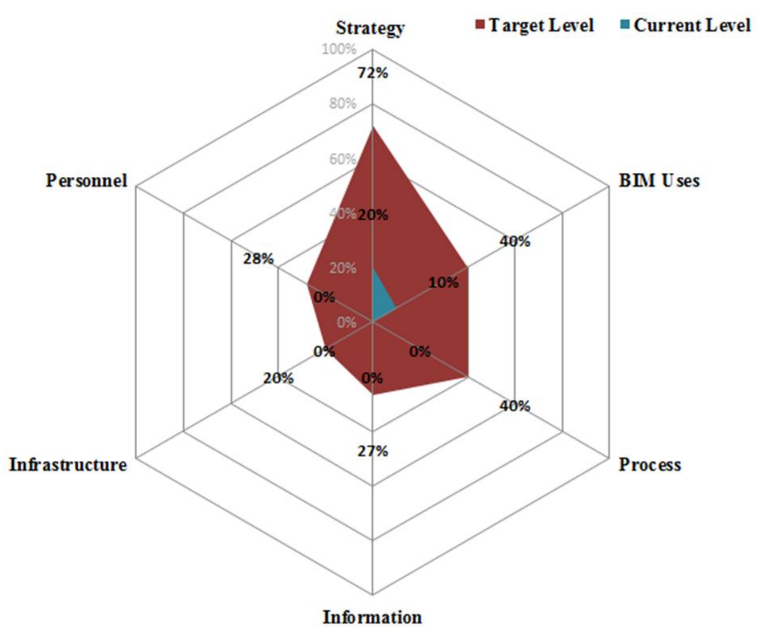


**Figure 1: BIM Assessment Profile**

**Working Meeting with the Organization**

The second meeting at the organization's office started with the discussion of BIM goals, BIM mission and vision of the organization. The BIM uses and the timeline for implementing them were also discussed. The different phases of a construction project and the BIM uses for those phases were categorized using post-it notes (Figure 2). The BIM Uses were finalized during the second meeting. A brief review of the contract language and the importance of having BIM language included were also discussed.

**Figure 2: CIC team member discussing the Strategic Plan**

After several meetings with the BIM champion and one of the managing directors of the organization, a BIM Strategic and Procurement Plan have been developed. The initial focus of this process was to develop a pilot BIM effort. Time and resource allocation for the BIM planning was not given much importance by the organization. The whole implementation process consumed considerable amount of time because of this reason.

## RESULTS OF PLANNING PROCESS

The following is a summary of the planning process including the BIM Organizational Strategic Plan and the BIM contract requirements.

**BIM Organizational Strategic Plan**

The Organization's mission for implementing BIM is to improve the efficiency of the design and construction processes from contracting to building turnover. The organization envisions using BIM to streamline the design and construction processes and implement BIM on all their projects. The goals and objectives of using BIM are shown in Table 4.

**Table 4: Goals and Objectives of the Organization**

| Goal | Objective |
|---|---|
| Improve design coordination | To have a completely coordinated design prior to construction during the design phase |
| Eliminate field conflicts | To use BIM to improve the coordination process therefore reducing the number of field clashes and conflicts to zero |
| To improve the visualization of space for potential clients | To use BIM to create a high quality visualization |
| To provide a realistic picture/representation of the facility for internal approval. | To require realistic visualization of the facility for design review |
| To provide a realistic picture/representation for external submissions. | When necessary, the organization may require visualization of the facility for the purpose of reviewing the design for approvals |

It is also the goal of the organization to improve communication through properly conveying the message and enabling a better understanding of contract requirements.

***BIM Uses***

The organization has identified the BIM Uses that would benefit them. The BIM uses were categorized into three phases based on how they want to implement them. Phase 1 BIM uses are for immediate implementation on the pilot project. The BIM uses which they want to implement on the pilot project are design authoring, construction coordination, and design review. After evaluating the uses on the pilot project they would like to implement them on all their other projects. These BIM uses will be standardized based on the results of the pilot project. Phase 2 BIM uses are the additional BIM uses which are not used on the pilot project. These are the uses which will be evaluated using additional pilot projects.

During Phase 2, Phase 1 BIM uses will be standardized. The implementation of Phase 2 uses will start during the second year. The list of uses the organization would like to implement is disaster planning, engineering analysis, compliance checking, programming, and existing conditions modeling. After evaluating Phase 2 BIM uses additional uses such as Record Modeling and Site Analysis will be added in Phase 3.

***Process, Information, Infrastructure and Personnel***

The process shows the ways in which BIM uses can be accomplished. The organization had neither external project BIM processes nor organizational BIM processes documented. It is targeting for an integrated high level process for both the project level and the organizational level. The organization has developed a list of basic information requirements for a project. They are consistent with a level of development 300 for design and level of development 400 for construction. The organization will not require any major infrastructure upgrades as part of this effort. However, in order to conduct detailed evaluations of the model it may require the purchase of standard BIM software. When adopting a new technology or processes, addressing the issues associated with personnel is often the most challenging. The organizational structure will not change based on BIM Implementation. It will be the responsibility of individual project managers to ensure that their projects are successfully implementing BIM to accomplish the goals set forth by the organization.

***BIM Roles and Responsibilities***

The BIM champion will be responsible for chalking out a plan for the organization. It is also the responsibility of the project manager of each project to take the responsibility. Few responsibilities of the BIM Champion include: developing, reviewing and updating the strategic BIM plan, developing and updating project procurement/contract language, developing organizational procedures and protocols, and educating and training personnel on BIM requirements. The BIM advocate/sponsor will support the efforts of the BIM champion and make resources available for the implementation of BIM as necessary. It is the responsibility of the project manager to understand the requirements of BIM contract language.

**BIM Organizational Procurement Plan**

Amendments were made to the existing contract language of the organization. Changes were made such that the new procurement language included all the required terminology relevant to the BIM Uses implemented in a project. The requirement of a Building Information Model along with the other 3D drawings was included in the contract language. Facility management data requirements was included along with other important product data such as manufacturer’s standard drawings, schedules, performance charts, test data, instructions, brochures, catalogs etc. The Level of Development (LOD) required at different phases of design, information needs and the roles and responsibilities of the personnel was included in the contract.

The most challenging aspect of the implementation of BIM will be to develop a culture of change within the organization. Devising a good strategic plan along with appropriation of resources is needed to support change within the organization. According to Shupe and Belhling (2006), successful deployment of technology requires support from higher management, a structured decision making process, and a strategy based on an understanding of the organization's vision. The team responsible for the development of strategic plan should comprise individuals representing all the functional units of the organization. This ensures that the strategic plan along with technology plan coincides with the mission and goals of the organization as a whole. This culture change will happen incrementally over years as each project begins to use the established BIM process. It is important to make sure that as new projects are procured with BIM contract language that the team members are educated and trained on what the requirements are so that there is a consistent message throughout the company.

# CONCLUSION

The case study of a real estate development organization was conducted for validating the different aspects of the BIM Planning Guide for Facility Owners. Strategic and Procurement planning elements of the organization were developed based on the guide. A graphical road map showing the time line and BIM use implementation would help the organization set goals for themselves and understand where they stand. During the process of the case study changes were made to the templates the CIC team developed based on the feedback and understanding of how it can more effectively reach the user. The size of the company will have an impact on the BIM implementation. As the size of the company increases the harder it is to develop a culture of change within the organization. But this aspect was not studied while conducting the case study.

Based on the case study, the lessons learned are as follows: It was understood that a proper amount of time should be allocated by the organization to develop a good strategic plan. Time and resource allocation were identified as two very major aspects which impact the strategic planning process. The organization should develop a road map of implementation which will help them achieve their targets within the timeline set by them. All major personnel in the organization should understand the motivation behind the BIM planning process. Lack of proper planning will delay the process of BIM implementation to a considerable amount of time.

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# A METHODOLOGICAL APPROACH TO IDENTIFY KEY PERFORMANCE INDICATORS AND MEASURES IN MAINTENANCE SERVICES IN INFECTION CONTROL

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**Abstract**
Hospital-acquired infections (HAIs) are a major problem in the United Kingdom (UK) and worldwide. The UK has one of the worst rates of hospital-acquired infections (HAIs) in Western Europe. One reason for such poor performance is the failure of healthcare officials to tackle the root causes of HAIs in the National Health Service (NHS). The position of healthcare officials is that HAI is mainly a clinical issue; requiring the attention of clinicians. As a result, most of the infection control policies and guidelines do not sufficiently address the non-clinical causes of HAIs in the NHS.

There is strong epidemiological evidence suggesting that HAIs can also occur because of the poor performance of facilities management (FM) services. An example of an FM service that has a strong link with HAI is healthcare maintenance. Despite being linked to such infections as aspergillosis, legionnaires etc, healthcare maintenance services (HMSs) in the NHS have nonetheless failed to attract the attention of healthcare authorities. In this study therefore, we examine the methodological approach in identifying the key performance indicators and measures in HMSs in infection control.

This study is divided into two main sections. In the first section, we examine different research paradigms, as well as, the rational for choosing interpretivism in this study. The second section, which is on the research design, examines the research methodology and research methods applied in this study. Addressing these methodological issues is important in identifying the key performance indicators and measures in HMSs in infection control.

**Key words:** HAIs, infection control, maintenance services, NHS, performance management

## 1. INTRODUCTION

The term Hospital-acquired infections (HAIs) usually means infections that were neither present nor incubating when a patient**,** visitor or hospital staff enters the hospital (National Audit Office - NAO, 2000). HAIs are a major problem to healthcare institutions throughout the world. In the United Kingdom (UK), it is estimated about 9% of inpatients acquire HAI at any one time during their stay in hospital (Parliamentary Office of Science and Technology, 2005). "*This means that at least 300 000 inpatients acquire an HAI each year — that is, 1 in every 11 patients admitted to hospital*" (Pratt, 2005: 1). In addition, HAIs constitute a huge financial drain on the scarce resources of the National Health Service (NHS). According to statistics released by the NAO (2004), the direct annual cost of HAI to the NHS is estimated at £1 billion. In addition, a further £55.7 million is incurred post discharge by general practitioners, outpatient consultants, and district nursing services (NAO, 2000).

The NAO (2004) estimates that through better infection control practices, the NHS could reduce the incidence of HAI by up to 15-30%. This could result in cost savings that could be used for alternative healthcare related priorities. For example, a 15% reduction in the rate of HAI could result to cash savings of up to about £150 million/year in the NHS (NAO, 2004). To reduce the prevalence of HAI and thus the cost associated with it, there is a need to adequately identify and address the root causes of HAI in the NHS.

Presently, it appears many healthcare authorities and researchers have identified clinical issues as the main causes of HAI. Most government publications in the UK rarely refer to the link between FM services and HAI. For example, in its publication entitled 'The Management and Control of Hospital Acquired Infection in Acute NHS Trusts in England' the NAO (2000) did not specifically mention the role of FM services in infection control. There is strong epidemiological evidence linking FM services like cleaning, waste management, laundry, catering, and maintenance services to HAIs. For the purpose of this study, it shall focus mainly on healthcare maintenance services (HMSs). This is because of the strong epidemiological link between HMSs and HAIs, and the fact that it has not been given enough attention. HMSs have been linked to aspergillosis, legionnaires disease etc (Centers for Disease Control and Prevention, 2003).

The lack of attention on maintenance-associated HAIs in the NHS is likely to contribute to the poor performance of HMSs in infection control. It appears there is a gap between the organisational strategy of the NHS in infection control, and that pursued by HMSs. This is because maintenance staffs appear to rely too much on their technical experience and behaviour (Lee and Scott, 2008). Most often, there is pressure on managers to reduce the cost of healthcare maintenance albeit to the detriment of infection control standards.

Despite the failure of healthcare authorities to recognise the role of HMSs in infection control, some Trusts have nonetheless formulated policies for the prevention of maintenance-associated HAIs. However, a review of some of these policies suggests wide variation in the number of infection control issues addressed. In addition, little is known whether these policies fully address the issue of infection control, and whether they are effectively implemented and realised by HMSs. According to Healthcare Facilities Scotland (2007), there is a problem with the effective dissemination and implementation of existing policies, guidelines etc in a logical and accessible form to all involved in the control of HAI in the NHS. Presently, it appears the clinical and nonclinical teams in the NHS are operating as though they were two separate entities (Liyanage and Egbu, 2005).

From the foregoing discussions, it is clear that improving the performance of HMSs in infection control will help the NHS reduce its current rate of HAIs. This study examines the methodology used to identify the key performance indicators (KPIs) and measures in infection control, which now appears lacking in HMSs in the NHS. This research is divided in to two main sections: research paradigm and research design (methodology and methods).

## 2. THE PARADIGMATIC POSITION OF THIS RESEARCH

This study focuses on the methodology that will be used to identify the key performance indicators and measures in HMSs in infection control. In this section, we discuss a number of issues related to the selection of the research paradigm in this research.

Research may be regarded as an investigation or inquiry in order to gather new information about a subject under study. Smith and Dainty (1991) define it as "*concerned with problem solving, investigating relationships and building on the body of knowledge*". In research, new facts and conclusions maybe discovered that eventually add or change the way things are done. To achieve a successful outcome in a research of this nature, it is necessary to have firm understanding of the assumptions surrounding the research framework. Also important is the understanding of the strengths and weaknesses of the research perspective (assumptions, values, and paradigms) to be adopted. According to Draper (2004), the relationship between philosophy and research influences the choice of research methodology to be adopted in a study.

Over the years, the strenuous journey by researchers to achieve knowledge has been achieved through different research paradigms (Kim, 2003). According to Guba and Lincoln (1994), research paradigm is "*a systematic set of beliefs, and their accompanying methods, that provide a view of the nature of reality*". It "*... describes the nature of the world, a person's place in it, and their relationship to the world*" (Guba and Lincoln, 1994). Notwithstanding the researcher's argument on how he/she visualises the world, Guba and Lincoln (994) contend that his belief must be accepted simply on faith. This is because of the difficulty of establishing ultimate truthfulness.

Because different inquirers view the world differently, it is clear that there will be divergent research paradigms. Although there are many research paradigms (i.e. the adversarial paradigm that guides the legal system, religious paradigm etc) the focus here is on those 'that guide disciplined inquiry' (Guba and Lincoln 1990). Historically, inquirers have focused predominantly on positivism to establish knowledge. However, over the years many contending paradigms have also emerged. These research paradigms can be categorised according to the way researchers provide answers to three fundamental questions relating to the epistemology, ontology, and methodology (Krauss, 2005). Also important are questions related to axiology and rhetorical structure (Ponterotto, 2005).

Broadly speaking, *"... ontology involves the nature of reality, epistemology addresses how we come to know that reality while methodology identifies the particular practices used to attain knowledge of it*" (Krauss, 2005: 758). Axiology concerns the role and place of values in the research process, while rhetorical structure relates to the language and presentation of the research (Ponterotto, 2005). All of these questions are interconnected in a way that the response to one question constrains the response to the other (Krauss, 2005). So far, the debate about research paradigms is focused on positivism otherwise called quantitative research and interpretivism otherwise called qualitative research. Also worth mentioning here is the mixed research paradigm, which is a combination of the quantitative and qualitative research methods.

The difference between positivism and interpretivism is an indication that researchers employ different research methodologies/methods in social sciences. As reiterated earlier, the debate about research paradigms in social sciences is primarily on positivism (aligned to quantitative research) and interpretivism (aligned to qualitative research). The difference between these two schools of thoughts is on their opposing assumptions about reality and view of the world. Whereas positivists believe in the existence of a single and measurable reality, interpretivists on the other hand believe in multiple realities and truths that are always changing, and difficult to measure (Sale *et al*., 2002).

The interpretivists reject the assumptions held by the positivists to treat social observations as entities in much the same way as physical scientists treat physical phenomena (Tuli, 2011). According to Guba and Lincoln (1994), the positivists' method of quantifying hypothesis, using mathematical formulas to predict and control natural phenomena has been questioned in the field of social science (Guba and Lincoln, 1994). According to early scholars like Dilthey (1894/1977), the goal of Naturewissenschaft (natural science) is scientific explanation, whereas the goal of Geisteswissenschaft (human science) is the understanding (verstehen) of social phenomena (Ponterotto, 2005).

The basic premise of interpretivism is that the researcher and the research participant should not be treated as individual entities existing in a vacuum, but rather as human beings. They are also to be treated as part of the research process. This is because 'reality' constructed in the mind of people can clearly be understood through an interactive researcher-participant dialogue (Ponterotto, 2005). It is also clear that research participants are the ones experiencing, processing, and labelling the 'reality' that is under investigation (Sciarra, 1999 cited in Ponterotto, 2005). The initial interaction between the researcher and research participant leads to deeper understanding of the social phenomena under investigation, and subsequent refinement of the research topic, questions, issues, design, and methods to be employed in a research project. The outcome is a process that adds richness and depth to the quality of data being collected (Tuli, 2011).

Following the above discussion, it can be said that the philosophical assumptions underlying this study will be situated within the realm of interpretivism. The research questions of this study are primarily concerned with providing an understanding of the performance of HMSs in infection control. According to Joubish *et al*. (2011), a research of this sort, concerned with developing explanations of social phenomena requires the close working relationship between researcher and research participants. The research participants of this research project shall be members of the infection control teams and facilities directors or assistants. Establishing a close working relationship with these research participants will enable these researchers see things from inside, rather than imposing a framework that may not be a reflection of the ideas of the research participants.

Many researchers i.e. Amaratunga *et al*. (2002); Thakkar *et al.* (2006), Zulkarnian *et al.* (2011), Peursem *et al.* (1995) who have conducted similar researches related also adopted the qualitative approach. The argument in favor of interpretivism does not mean that it is without criticisms. The fact that the values of the researcher and those of the participants are intertwined in the research process makes it difficult to ascertain complete objectivity and neutrality. In addition, the way participants understand social phenomena is often based on their individual experiences, memories and expectations (Guba and Lincoln, 1990). It is also likely that participants will vary their interpretation of the social phenomena with the passage of time. According to Heron and Reason (1997), such "*propositional knowing can only give mediated, subjective and inter-subjective, relativistic accounts*" of social phenomena.

# 3. THE RESEARCH DESIGN

The research design describes the overall plan action of how this research will be conducted in practice. According to Draper (2004), the research design is concerned with the practical arrangements of getting an answer to the research questions. Although the research design encompasses wide range of issues (ethical considerations, confidentiality etc), the focus of this section is on the research methodology and method that will be used to identify the key performance indicators and measures in infection control in HMSs. In this research, methodology will be defined as the "*strategy that translates ontological and epistemological principles into a set of guidelines showing how the research will be conducted*" (Sarantakos, 2005 cited in Tuli, 2010: 102. On the hand, methods will be defined as "*... techniques used to acquire and analyse data to create knowledge" (*Petty *et al*., 2012*).*

## 3.1 Research Methodology

Many research methodologies exist in qualitative research. However, only five of these are commonly chosen in human and social sciences: phenomenology, ethnography, narrative, grounded theory, and case study (Petty *et al*., 2012). Others include evaluation research, hermeneutics, feminism, action research, and participatory action research. Here, grounded theory was chosen as the preferred research methodology to meet the needs of this study.

### *3.1.1 Grounded Theory*

In-depth literature review on the above-mentioned qualitative research methodologies indicated that the study could best be conducted through grounded theory. Grounded theory has its root in sociology. It was developed by Glaser and Strauss from the University of California in the 1950s (Petty *et al*., 2012). According to Cope (2009: 647), grounded theory involves, at its heart, "*a set of strategies, tools, and central principles that aid researchers in doing inductive, reflexive, and rigorous analysis of data*". Although considered by many as an analysing technique, grounded theory nonetheless can be used in almost all the areas of the research. As Savenye and Robinson (1996: 1051) stated, it can be used "*to develop theory, through an iterative process of data analysis and theoretical analysis, with verification of hypotheses ongoing throughout the study*".

The application of grounded theory in this study is because of the degree of freedom and flexibility it gives researchers. For example, as new evidence emerges, the grounded theorist can move back and forth to adjust and refine key elements of the research. Moreover, unlike in other traditional qualitative methodological approaches, the research questions developed through the application of grounded theory are identified within a broad topic (Mehmetoglu and Altinay, 2006). The grounded theorist starts the research project with an open mind, whilst leaving room for discoveries.

As in grounded theory, the research materials used in this study were drawn from a wide range of sources. At the initial phase of this research, literature was drawn mainly from the University of Central Lancashire databases. These were primarily peer-reviewed journal papers. Preliminary analysis of the results emerging from the literature review led to the categorisation of these research materials into the following themes: FM, healthcare FM, HAIs, infection control, and performance management. The diversity of these themes meant that literature specifically related to these themes had to be drawn from multiple databases. Whilst research material relating to FM, healthcare FM and performance management were drawn from social sciences databases (i.e. Emerald), those relating to HAIs and infection control were drawn primarily from clinical research databases (i.e. PubMed, ScienceDirect). Additional data was also gathered from professional databases (i.e. Canadian Committee on Antibiotic Resistance, British Nursing Association etc) and government websites (e.g. Department of Health, Parliamentary Office of Science, and Technology etc).

The categorisation and analysis of the literature provided these researchers with further insight into the relationship between the five research themes already identified. In addition, it also led to the identification of some new themes and patterns. This included methodological issues, performance indicators, and measures. However, further literature review did not produce any additional themes or patterns. As a result, the mapping of the network relationship between the various research themes and patterns was conducted. This process led to identification of the research gap and problems, and the formulation of the aims and objectives of this study. The process also led to the development of the theoretical framework and the subsequent formulation of the research questions. In total, five main research questions and twenty-two interview questions were initially formulated.

Despite the usefulness of grounded theory, it is important for the researcher to avoid rigid coding and categorisation, as this that may lead to the fragmentation and decontextualisation of the data (Mehmetoglu and Altinay, 2006).

## 3.2 Research Method

The research method maybe described as the various methods/techniques used in the conduction of research. The four research methods employed in this study are literature review, document analysis, content analysis, and Delphi. However, for identifying the performance indicators and measures content analysis and Delphi were applied.

### *3.2.1 Content Analysis*

Content analysis is a qualitative and quantitative research method that used in "... *analysing written, verbal, or visual communication messages*" (Cole, 188 cited Elo and Kyngas, 2007: 107). There are two research approaches in content analysis: deductive and inductive. In the deductive approach, the researcher distils and condenses words into fewer content-related categories, in order to test theoretical issues and enhance understanding of the data (Elo and Kyngas, 2007). On the other hand, the inductive approach, the application of content analysis is the development of theory. It is similar to the constant comparison method proposed by Glaser and Strauss (Westbrook, 1994). This approach is recommended where knowledge is lacking or fragmented about the research phenomena under investigation.

This study was conducted using the inductive content analysis approach. This is because a search of the databases did not produce much information on performance indicators and measures in HMSs in infection control, especially related to the NHS. As a result, a search was conducted online for healthcare maintenance policies (HMPs). The Universal Dictionary (1987: 1194) defines policy "*as an overall plan or course of action adopted, as by ...business organisation* [hospitals], *designed to influence and determine immediate and long term decisions or actions*". According to Coetzee (1999), the maintenance policy is the most important (and foundational) area of the maintenance cycle. Strategically, the HMP is linked to the mission, and objectives of the NHS trusts. A review of the literature suggests that most HMPs were developed by the facility or maintenance department and approved by top management. It is about what management expects employees to do (Coetzee, 1999). In the case of the NHS, it will mean providing statutory compliance of HMSs in infection control.

As demonstrated above, HMPs contain valuable information that could be used to identify performance indicators and measures in HMSs in infection control. As the databases contained very little information on HMPs, the decision was taken to search the internet. Out of the fifteen HMPs obtained online, five could not be analysed because of inadequate information on infection control. The remaining HMPs were analysed through 'open coding', and words related to infection control grouped into various headings. A master list was then constructed, and the different headings categorised according to distinctive infection control areas – performance indicators. The master list also contained valuable information that was later used to identify performance measures. The eight performance indicators thus identified were maintenance resources, maintenance strategies, education/training, liaising/communication risk assessment, infection control practices, service level agreements, clients (healthcare users).

A count of the number of similar heading entered into each of these categories suggested that HMSs focus on maintenance strategies and service level agreement to manage their performance. Out of the ten HMPs reviewed here, nine and eight were on the healthcare maintenance strategy and service level agreement respectively. Unfortunately, this may not be due to infection control reasons alone. It appears the reason is mainly cost cutting. Ironically, the areas least covered by the HMPs included the training and education of maintenance staffs, infection control practices and clients. In their study on the performance appraisal of cleaning services in infection control, Liyanage and Egbu (2005) found that FM services rely too much on financial measures.

The performance indicators were then distributed according to the four performance metrics of the Balance Scorecard (BSC): finance (resources), internal business processes (maintenance strategies, risk assessment, infection control practices, liaising and communication, service level agreements), learning and growth (staff education and development), and customers (healthcare users). According to Banker *et al*. (2003: 423), the BSC is a popular performance management scheme that helps "*managers understand the interrelationships and tradeoffs between alternative performance dimensions and leads* *to improved decision making and problem solving*". One advantage of the BSC is that it allows management to focus on performance areas that are not directly link to bottom-line profits, but with future financial implications for the company. The performance indicators identified in this study are not directly linked to the financial profits of the NHS. However, improving the performance of HMSs in infection control could help the NHS reduce both the direct (i.e. litigation, treatment etc) and indirect cost (i.e. bereavement, transport etc) of HAIs.

### *3.2.2 The Application of Delphi*

In the next stage of this research, we identify the key performance indicators and measures of HMSs in infection control. This will be achieved through the application of Delphi. In the proceeding section, we discuss the different processes of Delphi that will be used to achieve the aforementioned aims.

*A. The Rationale for Selecting Delphi*

There appear to be debate amongst researchers concerning the paradigmatic position of Delphi. According to some authors, the epistemological and ontological position of Delphi is positivism. Their argument is centred on the fact that a researcher conducting a Delphi study can function in an objective and uninvolved observer. In addition, the researcher also utilizes quantitative methods to collect data, and applies single statistical measure to arrive at a 'consensus' (Hanafin, 2004).

On the other hand, some researchers view Delphi as being interpretative and qualitative in nature. According to Hanafin (2004), the process of iteration, which is inherent in a Delphi study, is in keeping with the interpretative paradigm. The ideas and opinions generated in a Delphi study are not formed in a vacuum, as often, the research participants have to listen to others' attitudes and understandings to focus on their own (Hanafin, 2004: 7). Such an interaction between the research participants is likely to produce rich data and insight that is less accessible, had the interaction not taken place. By treating the research participants as part of the research process, the researcher is able to grasp deeper understanding of the social phenomena under investigation. The focus of this study, which is in line with the interpretative approach, is therefore to grasps better understanding of the performance of HMSs in infection control.

Although Delphi started as a technique for futures research, it is currently being used by many researchers to deal with complex issues (Linstone and Turloff (1975 cited in Green *et al*., 1990). The fact that Delphi is an adaptable and flexible research method means that it can be applied across many disciplines (Skulmoski *et al*., 2007). Nonetheless, it is important for the researcher to make sure that it meets their research needs. According to Perez and Schuler (1982: 160), Delphi is appropriate in researches where there is the lack of solid information about the research phenomenon or problem under investigation. A thorough search of the databases did not produce many researches on the subject of performance management and infection control in HMSs in the NHS. Where researchers have examined the subject of performance management in the NHS, they have mostly focused on clinical issues and finance. This fact was also supported by the findings of the pilot study; conducted to refine the research questions. Most of the HM managers interviewed in the pilot study could not identify the performance indicators and measures in HMSs in infection control.

The results obtained from the pilot study indicated that interviews were unsuitable to answer the research questions put forth in this study. It therefore prompted the application of Delphi in this study. Unlike in interviews, Delphi allows the researcher to recruit professionals and "*focus their collective human intelligence on the problem at hand*" (Linstone and Turloff, 1975 cited in Skulmoski *et al*., 2007). Besides offering anonymity to respondents, Delphi also makes it possible for the researcher to recruit professionals from a wide geographical area. According to Kalaian and Kasim (2012: 2), this "*provides in-depth anonymous information about the problem or issue under consideration*". The application of Delphi in a study is not without its weaknesses. The reliability of a Delphi study is highly dependent on the quality of the research subjects, and technique employed to reach consensus (Hsu and Sandford, 2007). In the next section, we examine some of these issues.

### *B. The Selection of the Delphi Subjects*

The most important step in conducting a Delphi study is the nomination of the participants (Hallowell and Gambatese, 2010). This is because the credibility and reliability of Delphi studies depends on the quality of participants selected (Keeney *et al*., 2000). However, it appears there is no exact criterion listed in the literature for the nomination of Delphi participants (Hsu and Sandford). One criterion commonly used by researchers to select members of the Delphi panel is level of expertise. However, the characteristics used to define an individual as an 'expert' has been described as equivocal by Hallowell and Gambatese (2010).

Generally, the Delphi participants should be a person that is directly affected by the research, has knowledge and experience, and are facilitators in the field of study. Some authors contend that Delphi participants be selected based on authorship, conference presentations, committee membership etc. Irrespective of the nomination criteria employed in a study, care must be taken to ensure that the Delphi participants are unbiased, as this will likely affect the generalization of the results (Hallowell and Gambatese, 2010). Initially, healthcare maintenance managers (HMMs) were considered the best nominee for this Delphi study. However, they were excluded because they did not have the required knowledge to participate in this study. Evidence gathered from the pilot study suggests that many HMMs did not have basic knowledge on performance management and infection control issues. A vast majority of HMMs were not members of the infection control team or committee. Apart from ad hoc infection control practices to attain statutory compliance, many HMSs do not measure the performance of their services in infection control.

The Delphi subjects here are the directors or associate directors of NHS facilities and members of infection control teams (ICT). Unlike HMMs, directors of NHS facilities have adequate knowledge on environmental infection control issues. They are responsible for the hygiene standard of all FM services i.e. aspergillosis and legionella management, as well as, providing expert advice on new builds, refurbishment, and replacement programmes. On the other hand, the ICT is made up of a multidisciplinary team of microbiologists, nurses, doctors etc. They provide specialist advice, induction, education, and training of all NHS Trusts staffs in infection control related issues.

Another important issue when conducting a Delphi study is that of selecting the number of Delphi subjects. This study shall aim at nominating twenty Delphi subjects; ten directors of facilities and ten infection control personnel. There is presently no consensus of the optimum number of Delphi subjects in a study (Hsu and Sandford, 2007). However, Hallowell and Gambatese (2010) noted that the number of Delphi subjects be dictated by the characteristics of the study i.e. available experts, desired geographic location, and capability of the facilitator. Consideration also has to be placed on the fact that some subjects may decide to opt out of the study at a later stage.

*C. The Delphi Rounds*

According to Skulmoski *et al*. (2007), the number of rounds in a Delphi study is variable and depends upon the purpose of the study. Delbecq *et al*. (1975 cited in Skulmoski *et al*., 2007) noted that three round would be suitable for most studies. Nonetheless, this study shall have four rounds. The primary mode of iteration will be through email contact, and the Delphi subjects will be drawn from NHS Trusts across England.

Before embarking on the first round of the Delphi study, an informal meeting will be arranged with a number of facilities directors and members of the ICT at various NHS trusts across England. The purpose of the meeting will be to solicit participation in the Delphi study, by demonstrating the significance of the study in infection control. In addition, issues related to confidentiality will be discussed, and professionals asked to nominate colleagues for the study. After the informal meeting, a list of email addresses and contact information of the professionals will be compiled.

Typically, the first round of Delphi adopts an inductive approach where members of the panel are given a freedom to generate new ideas about the topic (Powell, 2002). Besides taking too much time to analyze, this approach has been criticized for not generating the level of rich information that a thorough literature review would otherwise produce (Millar, 2000 cited in Hanafin, 2004). It is therefore common practice to apply structured questionnaires, which are based on thorough literature review in the first round of Delphi (Hsu and Sandford, 2007). For the purpose of this study, semi-structured questionnaires will be used. Semi-structured interviews focus the attention of the panelists on the subject under discussion, and give them the freedom to generate new ideas. At the first round of the Delphi study, panelist are provided with a list of eight performance indicators (maintenance resources, maintenance strategy, infection control practices, Risk assessment, service level agreement, liaising/communication, training and education, customers) and asked to identify the performance measures in HMSs in infection control. In addition, open-ended questions will also be included for panelists to list additional performance indicators and measures or recommend changes to the original list.

The result obtained from the first round of the Delphi study will be used to refine the list of performance measures gathered through the literature review process. Each performance indicator will include lists of performance measures with a 5-point likert-type scale. These questions will then be used to probe panelists in rounds 2, 3, and 4. Consensus in each round of the Delphi will be achieved through the application of the inter-quartile range. However, in round three, panelists will also be asked questions related to the measurement of performance measures.

# 4. SUMMARY

Although the issue of infection control is often treated as though it is mainly a clinical issue, epidemiological evidence suggests that HMSs play a significant role. The primary aim of this study is therefore to examine the methodological approach in identifying the key performance indicators and measures in HMSs in infection control. The three methodological issues addressed here are research paradigm, research methodology and research methods.

An examination of different schools of thoughts indicates that this study is situated within the realm of interpretivism. This is because the identification of the key performance indicators and measures in HMSs in infection control is best understood with the researcher working closely with those experiencing and shaping the event. Having identified the paradigmatic position of this research, the next step in the research process was to select an appropriate research methodology and research methods to investigate the performance indicators and measures. Grounded theory was chosen as the preferred research methodology. Unlike in other qualitative research methodologies, grounded theory provides the researcher with the possibility to identify and refine key aspects of the study as he/she progresses. Through the application of grounded theory, we were able to identify a number of issues including the research gap, research problems, research questions etc.

The identification of the performance indicators and measures from HMPs was conducted using content analysis. The eight performance indicators identified were maintenance resources, maintenance strategies, education/training, liaising/communication risk assessment, infection control practices, service level agreements, clients (healthcare users). Initially, the questions used in the pilot study were developed from the process of grounded theory and content analysis. Analysis of the result of the pilot study revealed that healthcare maintenance managers have insufficient understanding of performance management and infection control. This indicated that interviews could not be used to solicit the kind of rich information required to answer the research questions set here. As a result, Delphi was selected to identify the key performance indicators and measures in HMSs in infection control. In the next stage of this study, the key performance indicators and measures will be used to develop a balanced scorecard performance matrix.

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# USE OF MECHANICAL COUPLERS IN CONCRETE COLUMNS

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## ABSTRACT

This paper investigates the seismic performance of a two-column bridge bent with a primary focus on the mechanical couplers used to connect the reinforcement bars at the base of the columns. Previous research has focused on the need to properly account for at-yield and post-yield tensile behavior of these connections, but little has been done in the area of research into the use and detailing of these couplers subjected to the compressive forces in the region of plastic hinges. To study the behavior of the mechanical couplers in compression, a two-column bridge bent was tested at the University of California, San Diego. In the test, mechanical couplers were used to attach the longitudinal reinforcement bars at staggered heights in the plastic hinge zone at the base of the columns in a manner that was similar to a prototype. The results of the test indicated that current design practices are inadequate to properly develop the necessary compressive forces in the reinforcement bars in these types of connections. Moreover, while the couplers in the test performed adequately, the compression region of the column became unstable due to the buckling of the steel reinforcement around the location of the couplers. This paper describes a shortcoming of the current methodology, along with solutions to provide a plastic hinge capable of delivering additional ductility during seismic events.

**Keywords:** bridge; column; ductility; earthquake-resistant; flexural strength.

## INTRODUCTION

Mechanical couplers have been used to extend steel reinforcement in concrete columns and beams for a long time. When installed correctly in seismic applications, couplers are designed so that the steel reinforcement fails at the ultimate tensile load of an otherwise bare bar and to prevent failure in the mechanical coupler. While the tensile testing of mechanical couplers has been extensive, the testing of mechanical coupler installations that may be in compression in plastic hinge regions of a column or beam is absent.

In a heavily reinforced column or beam, mechanical couplers are staggered to avoid or reduce both stress concentrations and steel congestion as shown in Fig. 1.

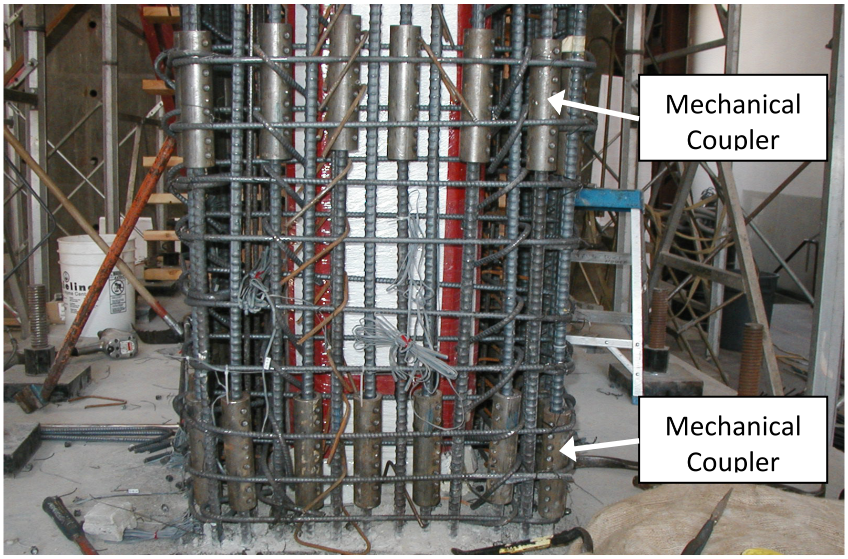


**Fig. 1: Reinforcement Cage with Mechanical Couplers**

With this staggered condition in mind, consider the two sections of a column in Fig. 2, wherein Section A has mechanical couplers and Section B does not have mechanical couplers.

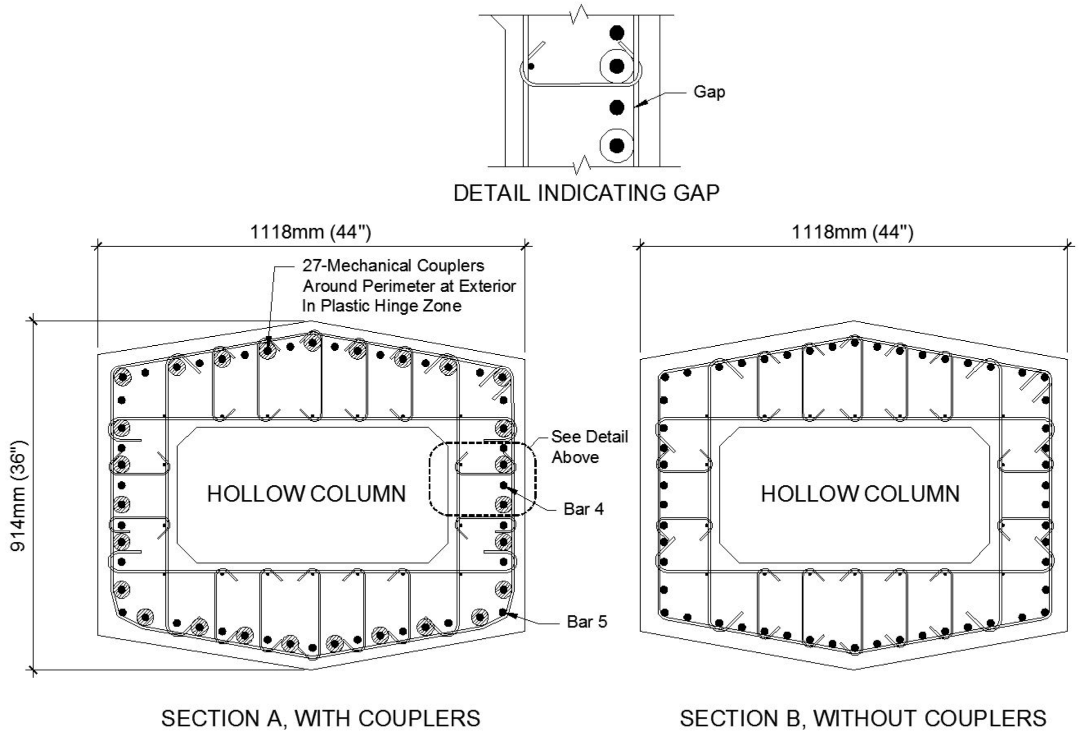


**Fig. 2: Column Section With and Without Mechanical Couplers**

Note that there is a gap between the transverse restraining reinforcement in Section A and the longtitudinal reinforcement without couplers.

The design of the section makes it readily apparent that prior to yield and at low ductility levels where the concrete is intact or has not spalled, that the buckling of the compression reinforcement is not an issue. However, at higher levels of ductility wherein the concrete cover has spalled, only a small portion of concrete between the the transverse restraining reinforcement and the braced longitudinal reinforcement remains. If the small portion of concrete is removed then the longitudinal reinforcement is unbraced over a much greater length and buckling can and probably will occur.

In the case noted above, the use of staggered mechanical couplers may result in a reduced ductility of the concrete member. Consider the following:

- Columns that are designed to current standards without mechanical couplers have a very high ductility without the buckling of the longitudinal reinforcement.

- The longitudinal reinforcement did not buckle in regions where mechanical couplers in the column were located outside the plastic hinge region.

- When mechanical couplers were located in the plastic hinge region, the longitudinal reinforcement adjacent to the mechanical couplers buckled.

- The testing of additional support devices (such as additional support ties or bracing mechanisms) for the bars adjacent to mechanical couplers in the plastic hinge region has been overlooked.

To investigate the inclusion of mechanical couplers in columns, two columns were tested simultaneously in a quasi-static test that indicated via strain gages that a supported corner bar received more strain (and therefore more stress due to strain hardening) than an unsupported interior bar.

## RESEARCH SIGNIFICANCE

Use of mechanical couplers in the plastic hinge region of a column or beam can result in a reduced ductility of a concrete structure. In an experimental investigation, mechanical couplers were installed on the longitudinal reinforcement of two columns. The typical installation of the mechanical couplers in the plastic hinge region created a condition wherein the adjacent compression reinforcement without couplers was effectively "unsupported" since the bars were offset from the restraining transverse reinforcement by the thickness of the shell of the coupler. The offsets between the unsupported bars and transverse reinforcement were filled by a small amount of concrete when the columns were poured. At higher levels of ductility, the offset allowed for a stability issue to arise when the concrete that filled the offset deteriorated and spalled away. In both columns tested, the compression reinforcement buckled at the same location of the mechanical couplers even though transverse reinforcement had been installed to resist buckling.

## COLUMNS WITHOUT COUPLERS

As noted in Priestley (1996), there are two possible modes of buckling for compression reinforcement in the plastic hinge region. The first mode of buckling occurs when the compression reinforcement buckles between the layers of tranverse reinforcement. In order to avoid buckling between the layers, the longitudinal reinforcement must be of an adequate diameter to provide the required strength to resist buckling. The first antibuckling requirement for this type of buckling is given in ACI318-11 (2011) as:

$$s \leq 6d_{bl}$$

The second mode of buckling occurs when the longitudinal reinforcement buckles over several layers of transverse reinforcement. The antibuckling requirement for the second mode consists of transverse reinforcement capable of restraining longitudinal compression reinforcement against buckling. In Priestley (1996), the area of transverse reinforcement required to restrain the longitudinal bars is given as:

$$A_{tr} \approx \frac{\sum A_l s}{100 d_{bl}} \frac{f_y}{f_{yh}}$$

In ACI318-11 (2011), the area of transverse reinforcement for special moment frames is given as:

$$A_{sh} = \max \begin{cases} 0.3 \dfrac{s b_c f_c^{'}}{f_{yt}} \left[ \left( \dfrac{A_g}{A_{ch}} \right) - 1 \right] \\ 0.09 \dfrac{s b_c f_c^{'}}{f_{yt}} \end{cases}$$

Based on previous research, columns held to the above standards provide reasonable protection and ductility to the plastic hinge regions of columns.

## EXPERIMENTAL INVESTIGATION

In the experimental investigation performed at the University of California, San Diego, two columns (North Column and South Column) were tested simultaneously in a quasi-static test where two levels of mechanical couplers were installed as shown in Fig. 1. The upper layer was installed thirty inches from the column/foundation joint and the lower layer was installed six inches from the column/foundation joint. The lower layer of mechanical couplers was located entirely inside the plastic hinges at the base of the columns. Both columns were well instrumented with linear variable displacement transformers and strain gages. The strain gages were installed in numerous locations on the steel reinforcement inside each of the columns.

The two-column specimen was quasi-statically loaded through cycles in the both the push and pull directions. For the data noted below, the push cycle represents compression in the column noted, and the pull cycle represents tension.

To begin the test, the lateral force was increased from zero to 100 percent of the predicted yield force (force control) in 25 percent increments. Later, once the yield force was reached, the displacement was increased as an increment of the ideal yield displacement (displacement control).

**Mechanical Couplers Outside of the Plastic Hinge Region**
A review of strain gages in the region above the plastic hinge indicated very low strains in the transverse hoop reinforcement and the bar ties at the largest displacements of the columns. Photographic observations from the test confirmed that the area outside the plastic hinge did not have any spalling around the mechanical couplers and therefore the inclusion of the mechanical couplers had virtually no effect on the performance of the columns.

**Mechanical Couplers Inside of the Plastic Hinge Region**
For the mechanical couplers inside of the plastic hinge region, the testing of the columns progressed: through initial cracking, to yielding of the tensile bars, to spalling of the compression concrete cover, and to the final buckling of the compression reinforcement. The testing was concluded when the resistive strength of the specimen fell below 80 percent of the ultimate strength. In the plastic hinge region, two longitudinal bars with strain gages in the South Column, bars 4 and 5, (shown in Fig. 2) were used to obtain data that is described below.

Evidence of buckling of the unstabilized bar 4 versus the stabilized bar 5:

1. Strain gage data for an unstabilized bar and a corner bar which is stabilized by position are compared. In Fig. 3, the strain history of the two bars are shown where a positive strain indicates that the bar was in tension and a negative strain indicates the bar was in compression. What is apparent is that between the 6-inch and 9-inch positive displacement compression cycles, that the concrete spalls at the compression face resulting in a redistribution of the load from the concrete to the steel reinforcement.

2. At the 12-inch positive displacement in Fig. 3, note that there is a large difference between the strains in the response history of bars 4 and 5. As the redistribution of the load from the concrete to the steel reinforcement continued, there was a large increase in the strain of bar 5.

3. In the photo of the 12 inch positive displacement, Fig. 4, note how the expansion of the concrete core has pushed the external concrete shell outward as a sheet of concrete. This expansion in large part had been caused by the buckling of the compression reinforcement. At the end of the test, the magnitude of the buckling can easily be seen.

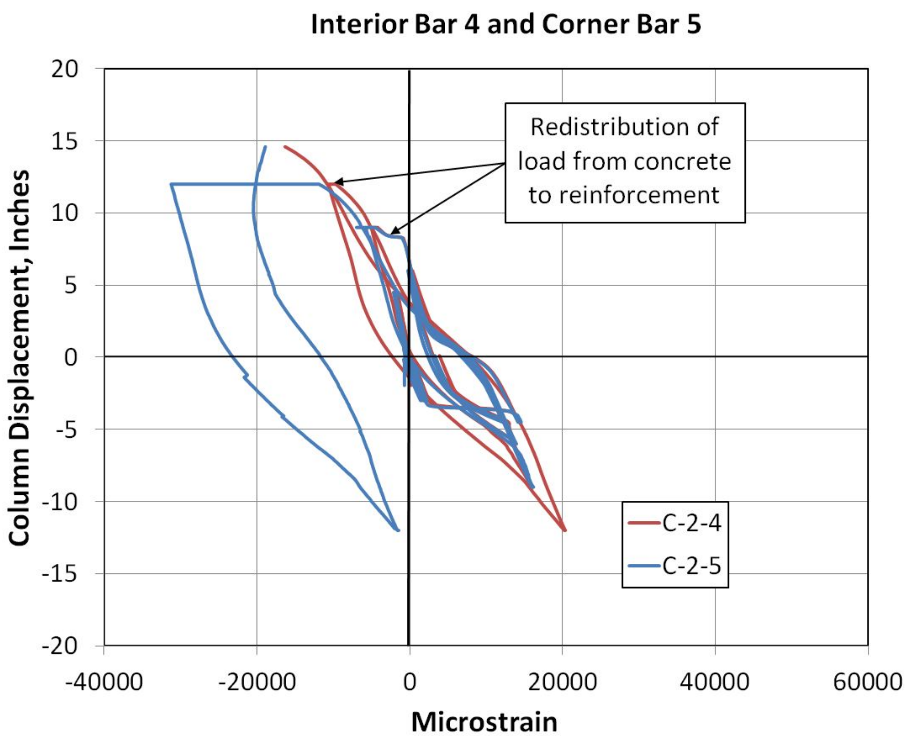


**Fig. 3: Comparison of Strain in Bars 4 and 5 versus Drift**

4. In the post-test inspection of the concrete core (shown in Fig. 5) where all the loose shell concrete had been removed, note how the unsupported compression reinforcement bars, which started out aligned with the supported mechanical coupler bars, bowed outward to be in contact with the transverse reinforcement. This movement was because the concrete, which at one time was between the unsupported longitudinal reinforcement and the transverse reinforcement, had been dislodged during the loading cycles.

**Options for Mechanical Couplers Inside of the Plastic Hinge Region**

A way to possibly prevent ductility loss due to unsupported bars may be the addition of metal spacers that attach the longitudinal reinforcement to the transverse reinforcement in order to fill the offset gap. However, this solution has not been tested and other problems related to stress concentrations may occur since the steel reinforcements just outside of the mechanical couplers would be much less stiff than the couplers. An example of a stress concentration can be seen in a photograph of the North Column, Fig. 6, where the steel reinforcement fractured just outside of the mechanical coupler.

Another way to possibly prevent ductility loss may be the addition of cross-ties that specifically anchor the unsupported longitudinal reinforcement. However, this solution may lead to steel congestion in addition to the stress concentrations that may occur.

**Fig. 4: South Column at 12-Inch Positive Displacement**

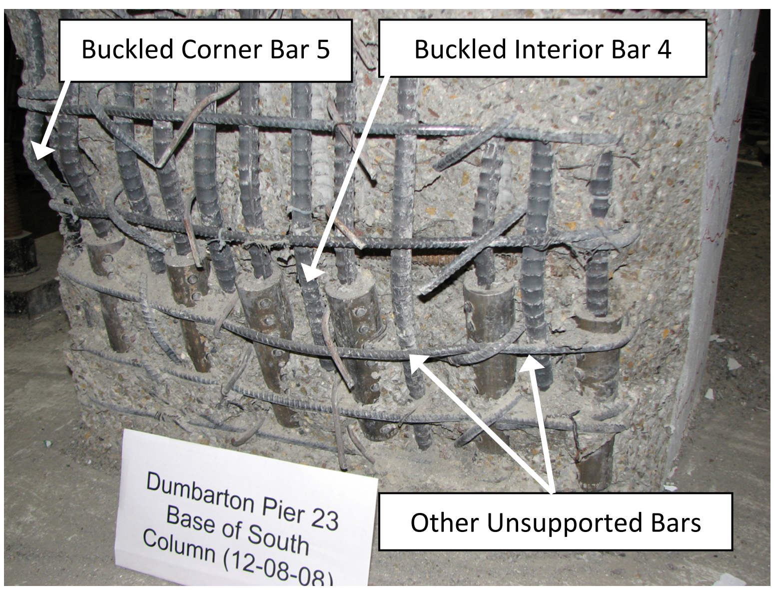


**Fig. 5: South Column - Buckled Compression Bars**

## CONCLUSION

It is not necessary to locate mechanical couplers in the plastic hinge region of columns and beams in a typical installation, however the extension of the reinforcement beyond the plastic hinge region may be inconvenient. And while the findings provided in this paper are related to only one test specimen with two columns, it should not be assumed that the condition is isolated.

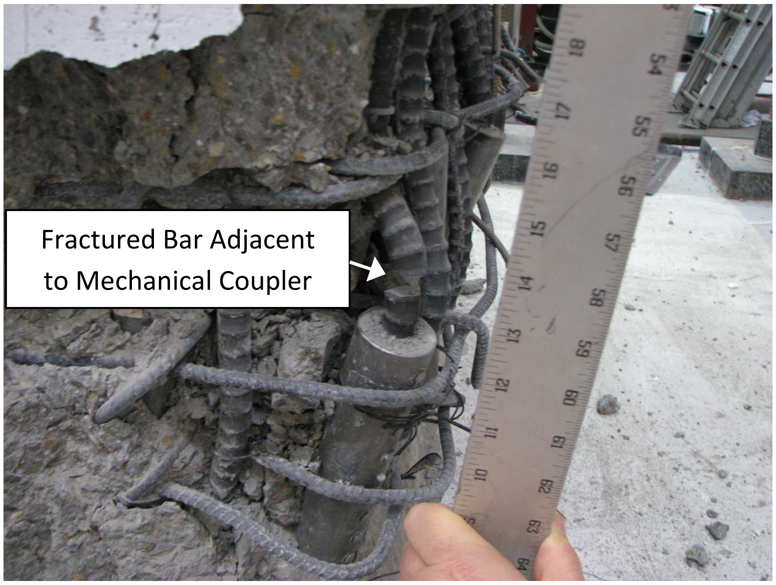


**Fig. 6: North Column - Fractured Longitudinal Bar**

Note that the experimental investigation did not include the total amount of transverse reinforcement as required by current standards, however the gap between the transverse reinforcement and the longitudinal reinforcement is still problematic and the stress concentration that is created by the mechanical couplers should not be overlooked.

In the case of this investigation, the mechanical couplers were staggered as required by the local authority to reduce steel congestion in the plastic hinge. However, it is often the case that steel congestion is not an issue and all mechanical couplers in these relatively lightly reinforced columns or beams are installed at one level. This condition is not addressed in this paper.

Note also, that the mechanical couplers that were installed on the longitudinal reinforcement worked as designed so that the steel reinforcement failed prior to any observed damage to the coupler.

Based on the experimental investigation it is concluded that:

- Due to lower compression stresses and the lack of spalling, the longitudinal reinforcement did not buckle in regions where mechanical couplers in the column were located outside the plastic hinge region.

- It may be problematic to locate mechanical couplers in columns and beams in the plastic hinge region, where those couplers are staggered.

## FUTURE RESEARCH

Further research in the use of mechanical couplers in plastic hinge regions is required. Mechanical couplers that were located outside of the plastic hinge performed well, while those in the plastic hinge region were indirectly responsible for the buckling of adjacent non-coupled reinforcement.

## ACKNOWLEDGEMENTS

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## NOTATION

$A_{ch}$ = cross-sectional area of the structural member core as measured to the outside edges of the transverse reinforcement, $in^2$.
$A_g$ = gross area of concrete section, $in^2$.
$A_l$ = area of longitudinal reinforcement, $in^2$.
$A_{sh}$ = total cross-section area of transverse reinforcement, $in^2$.
$A_{tr}$ = area of transverse reinforcement to restrain longitudinal reinforcement, $in^2$.
$b_c$ = cross-sectional dimension of the structural member core as measured to the outside edges of the transverse reinforcement composing $A_{ch}$, $in^2$.
$d_{bl}$ = diameter of longitudinal reinforcement, in.
$f_c'$ = ultimate compressive stress of the concrete, ksi
$f_y$ = yield stress of longitudinal reinforcement, ksi
$f_{yh}$ = yield stress of transverse hoop reinforcement (equals $f_{yt}$), ksi
$f_{yt}$ = yield stress of transverse tie reinforcement, ksi
$d_{bl}$ = diameter of longitudinal reinforcement, in.
$s$ = center-to-center spacing of transverse reinforcement, in.

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# RACKING PERFORMANCE ANALYSIS OF FOUR-SIDED STRUCTURAL SEALANT GLAZING CURTAIN WALL SYSTEMS THROUGH VIDEO CAPTURE TECHNIQUE

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## ABSTRACT

Full-scale "unitized", four-sided structural sealant glazing (4SSG) curtain wall system mockups featuring a re-entrant corner were subjected to cyclic racking displacements in accordance with the American Architectural Manufacturers Association AAMA 501.6 protocol to determine serviceability and ultimate behavior responses. Glass fallout, sealant adhesive or cohesive failure, and glass cracking were identified as limit states and corresponding drift levels were determined. This paper describes the details of the techniques developed and used for analysis and shows example applications of the method to mockups with racking test results available. The video analysis measured the changes in distances between glass and frame, which was then used to calculate an effective shear strain of the structural silicone by a linear and quadratic method. An effective shear strain of 173% and 130% was calculated from a linear method and a quadratic method for a structural silicone when failure initiated. Test data from the manufacturer indicates the ultimate shear strain of the structural silicone occurs around 200%.

## KEYWORDS

Curtain Wall, Glazing, Dynamic Racking Test, Structural Sealant Glazing, Video Analysis

## INTRODUCTION

There have been several studies on the racking performance of curtain wall systems. However, a literature review shows that only a pilot study reported in Memari et al. (2012a) has used video footage for analysis of the racking performance. This paper represents a portion of the thesis study in Simmons (2011). The objective of the part of the study reported here was to confirm the assumed in-plane movements of the glass relative to the frame due to racking and to calculate the effective shear strain and the rotations of the glass and frame using video analysis. The extent of damage to sealant joints was tracked as a function of drift level through visual and video inspection of structural sealant. The information presented in this paper is useful in developing a better understanding of the behavior of 4SSG curtain wall systems for seismic design. The intent is to avoid a trial and error method of designing a 4SSG curtain wall system. This is significant, since the AAMA 501.6 testing process takes time and consumes resources.

## DISCUSSION OF PHYSICAL TESTING

The physical testing of the mockups was performed as part of a project of which this paper forms a portion of the analytical component. Memari and Kremer (2012c) provide details of the physical testing in a separate report. The following is a description of the constants, variables, observations, and conclusions from that report.

The dynamic racking test facility (Figure 1) used for the experiment consists of two horizontal-siding tubular steel beams, which represents spandrel beams on adjacent stories of a multi-story building. Each specimen was anchored to the sliding tubular beams at the mullions. A hydraulic ram (not shown in Figure 1) drove the bottom beam, while the top beam was coupled to the bottom beam by means of a fulcrum and pivot arm assembly.

The testing consisted of three identical mockups (Figure 1). The panels were glazed with Dow Corning 983 Structural Glazing Sealant in 2010. Mockup A is not reported in this paper. Mockup B was tested with a stick-built boundary condition and mockup C was tested with a stick-built-with-vertical-slip condition. As a result, the behavior of Mockup B was somewhat pure-racking, whereas Mockup C allowed for the panels to slip vertically past each other. The basic dimensions of all of the mockups are shown in Figure 2.

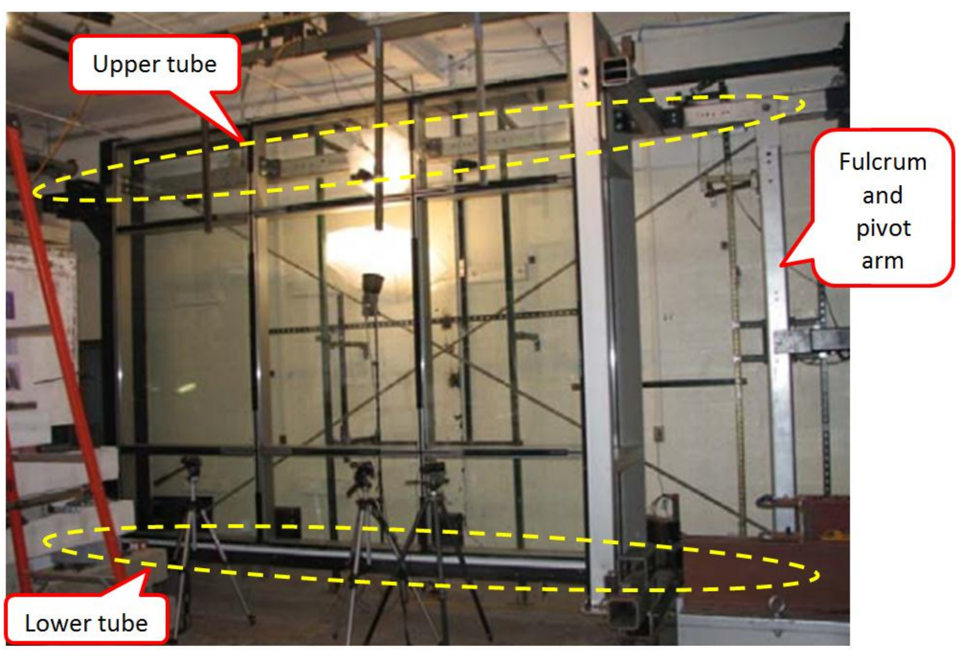


**Figure 1 – Typical Mockup Mounted on the Racking Test Facility**

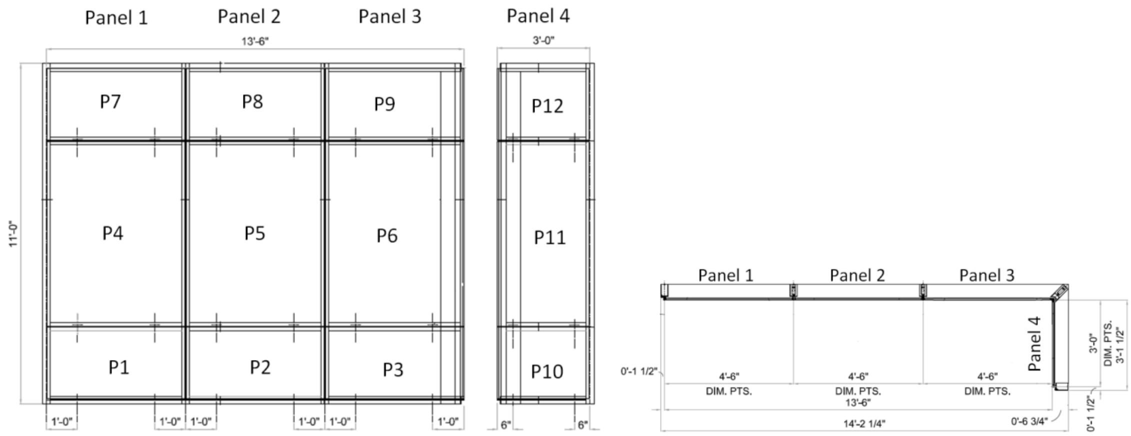


**Figure 2 – Elevation and plan view of three panels and a perpendicular panel of a 4SSG curtain wall system (recreated from drawing provided by Bagatelos Architectural Glass Systems Inc.)**

The failure modes of the mockup are defined are similar to those in Memari et al. (2006, 20011 and 2012b). Serviceability failure includes glass cracking or air leakage due to weather-seal and/or structural seal failure. An ultimate failure is when a piece of glass, at least 1 $in^2$ in size, falls out from the mockup. The racking tests followed the procedure outlined in AAMA 501.6 (2009), according to which the racking drift vs. time, is induced in ¼" drift amplitude steps. In this research study, the racking was stopped after each ¼" step for inspection of any structural sealant damage. Figure 3 depicts this drift vs. time for step 12 (maximum nominal amplitude of 3") and highlights the positive and negative amplitudes during the sixth cycle, labeled as C6.25 and C6.75. These are the targeted instants during the test for the video analysis.

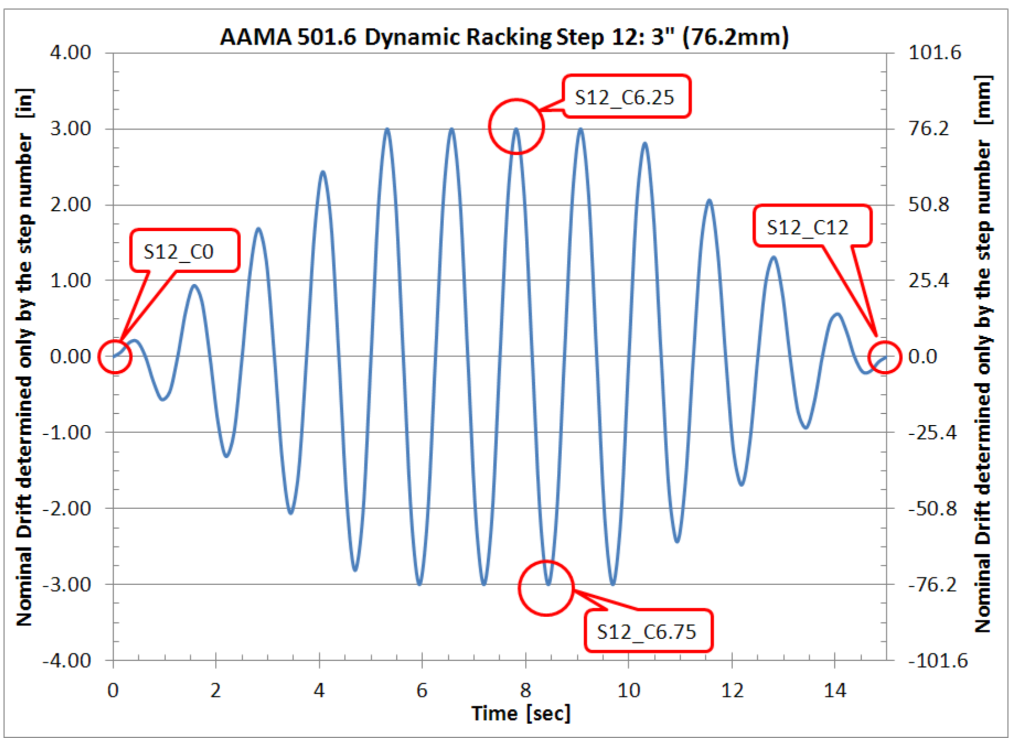


**Figure 3 – Drift vs. Time for Dynamic Racking Step 12 (Modeled after AAMA 501.6 2009)**

## VIDEO ANALYSIS OF RELATIVE MOVEMENT

Video camcorders were focused on the intersections of mullions with transoms of the curtain wall panels. A technique was used to measure the movement of the glass corners relative to the mullions and transom. The technique was to view the video recordings frame-by-frame, take screen shots of the undeformed position and the maximum deformed position at C6.25 and C6.75 for selected steps, and import the images into AutoCAD to scale and take measurements (Figure 4).

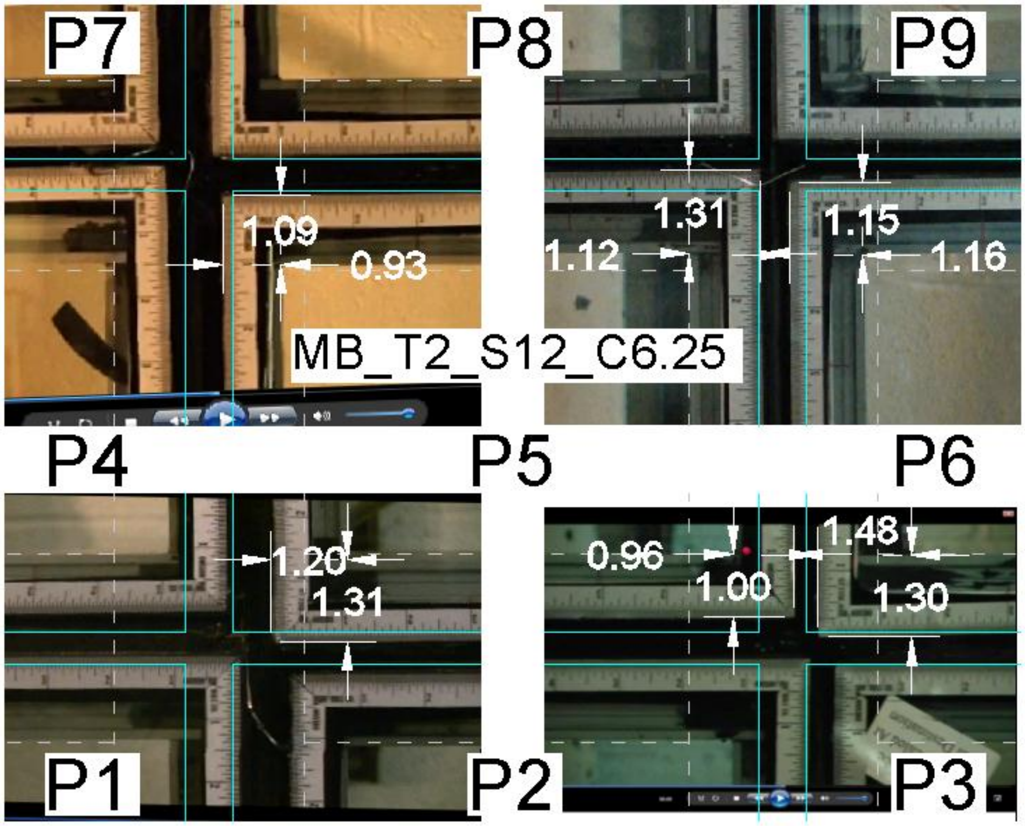


**Figure 4 – Screen shot of four intersections of Mockup B during Step 12 at Cycle 6.25**

Capturing, preparing, and measuring the images can be tedious and time consuming. As a result, it was only executed for two amplitudes for any given AAMA 501.6 step (C6.25 and C6.75 of Figure 3). The video analysis measures the horizontal and vertical distances from the corner of a glass pane to a corner of an intersecting mullion and transom. The change in these distances from the undeformed shape to the deformed shape (C6.25 or C6.75) is then divided by the thickness of the structural sealant to calculate the longitudinal shear strain (Δr / thickness) and transverse shear strain (Δs / thickness) of the structural sealant. These values are used to calculate the effective shear strain (Δt / thickness) based on two methods. The first method is a linear relationship of longitudinal shear plus transverse shear. $\Delta t = |\Delta r| + |\Delta s|$. This is based on an equation from Shisler and Klosowski (1990). The second method is a quadratic relationship of the square root of the sum of longitudinal shear squared plus transverse shear squared. $\Delta t = \sqrt{\Delta r^2 + \Delta s^2}$. This is based on an equation from Sandberg and Ahlborn (1989).

**Mockup B Test 2: discussion of results**

Figures 5 to 8 show calculated strain values at the corners of glass panes 4, 5, and 6. The legend on the figures identifies the glass pane number and the corner that the measurements were taken from. The calculated effective shear strain by each method is presented in Figures 5 and 6 for cycle 6.25, and presented in Figures 7 and 8 for cycle 6.75. The x-axis of Figures 5 to 8 is the scalar sum of the independently measured displacements at the upper and lower tube, which represents an inter-story drift. These displacements are always slightly less than the nominal displacement of any given step for the AAMA 501.6 test, due to flexibilities in the testing apparatus. Data points for three of the locations are not shown for step 21 due to observations of structural sealant failure at those locations and a dramatic increase in the calculated strain value. Data is not shown for steps 22, 23, or 24 due to extensive structural sealant failure.

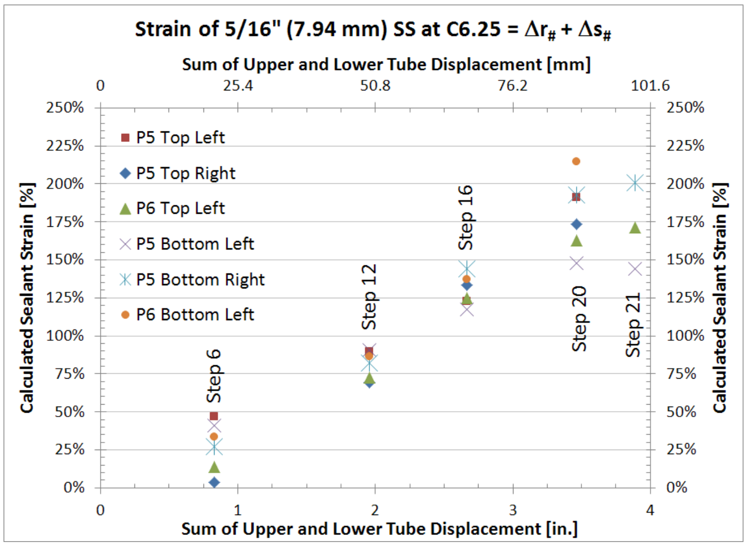


**Figure 5 – Calculated (Method 1) strain vs. displacement of Mockup B Test 2 Cycle 6.25**

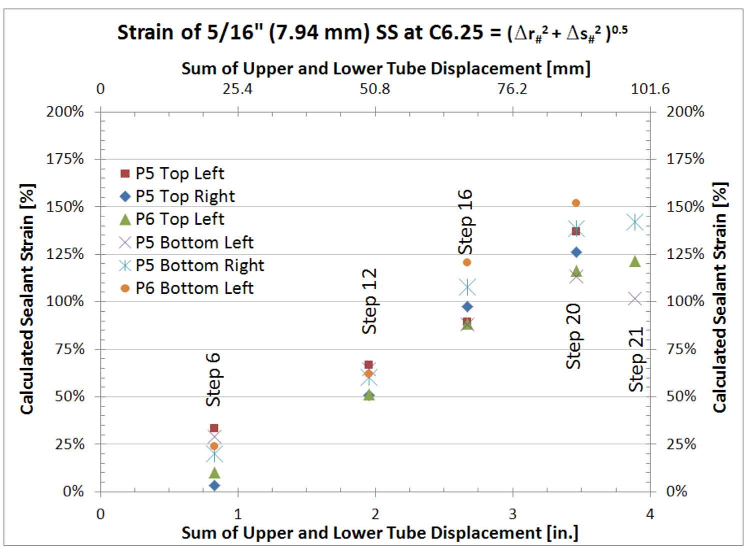


**Figure 6 – Calculated (Method 2) strain vs. displacement of Mockup B Test 2 Cycle 6.25**

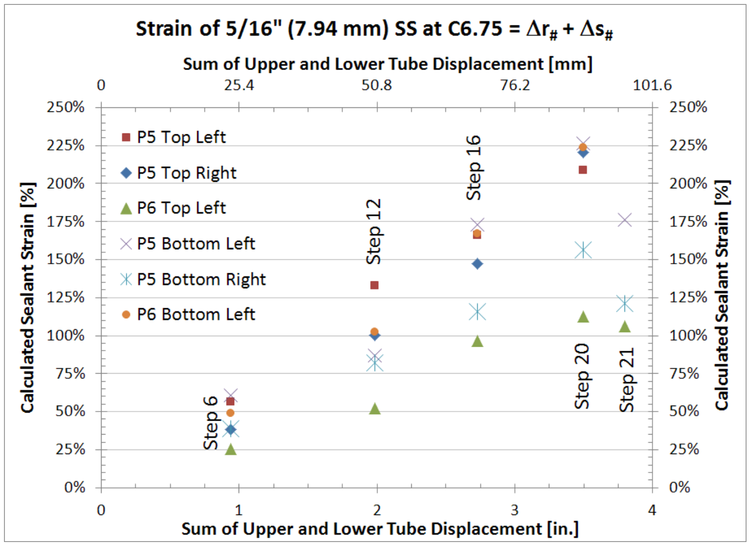


**Figure 7 – Calculated (Method 1) strain vs. displacement of Mockup B Test 2 Cycle 6.75**

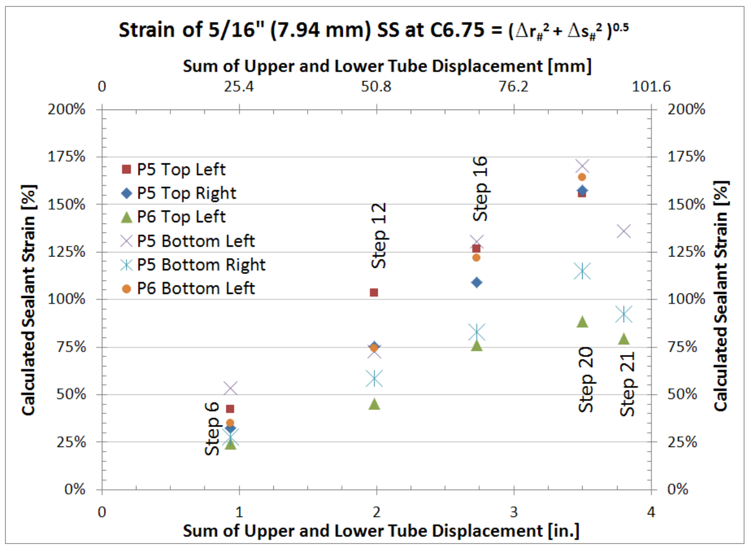


**Figure 8 – Calculated (Method 2) strain vs. displacement of Mockup B Test 2 Cycle 6.75**

Structural sealant failure was first noted after step 16 at the bottom left corner of glass pane 6 (P6_Bottom_Left). The failure was described as a 3/8" long tear, which was ¼" deep. From the video analysis at step 16, the calculated strains for cycle 6.75 were at P6_Bottom_Left with values of 167% from method 1 (Figure 7) or 122% from method 2 (Figure 8). Test data in accordance with AC45 (ICBO 1991) from Dow Corning of the 983 Structural Glazing Sealant indicates an ultimate shear strain limit of approximately 190% to 200%. This suggests that the linear method is more appropriate to describe the strain limits. However, note that at step 16 the maximum strain occurred at P5_Bottom_Left with values of 173% from method 1 (Figure 7) or 130% from method 2 (Figure 8). It is assumed that a defect in the structural sealant bead near the bottom left corner of glass pane 5 led to a premature failure, since failure was noted at P6_Bottom_Left, but not P5_Bottom_Left and the failure occurred below the ultimate shear strain limit. The maximum calculated strain values for step 20 occurred at cycle 6.75, which are 226% according to the linear method (Figure 7) and 170% according to the quadratic method (Figure 8). Since structural sealant failure was observed at the following step, this also suggest that the linear method is more appropriate to describe the strain limits.

Figures 5 to 8 also show that the calculated strains are greater at a negative drift (C6.75) than at a positive drift of the mockup (C6.25). The re-entrant corner of the mockup creates an asymmetry, which is a likely source for the differences between the positive and negative drifts. To quantify this difference, the calculated strains for each step were averaged and plotted (not shown here) to compare the difference between the two cycles. The data points are relatively linear up to step 20; however a linear regression line has an x-axis-intercept of approximately 7/16" for C6.25 data and 3/16" for C6.75 data. This implies that once the mockup reaches an amplitude displacement and returns to its initial displacement of zero, it must be displaced about +7/16" or -3/16" before the structural sealant returns to an undeformed position. This could be a result of flexibilities in the steel angles that connect the mockup specimen to the sliding tubes of the testing apparatus. In addition, the mockup specimen itself may have some flexibility, which allows for the transoms and mullions to deform without any significant strains of the structural sealant.

## Mockup C Test 2: discussion of results

Mockup C is the same as Mockup B except the boundary condition allows for the panels to slip vertically past each other. Figures 9 to 12 are plots of calculated strain values at the corners of glass panes 4, 5, and 6. The calculated effective shear strain from each method is presented in Figures 9 and 10 for cycle 6.25, and presented in Figures 11 and 12 for cycle 6.75. The maximum calculated strain values during step 24 occurred at cycle 6.75 which are 270% according to the linear method (Figure 11) and 198% according to the quadratic method (Figure 12). Structural sealant damage was not observed at this drift. Thus the quadratic method apears to be more appropriate to describe the strain limits, because the linear methos is predicting an effective shear strain that much higher then the 200% ultimate shear strain of the sealant.

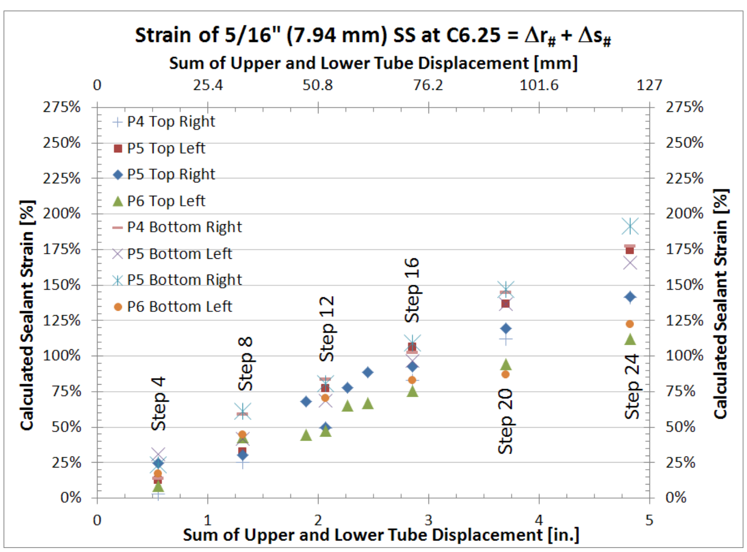


**Figure 9 – Calculated (Method 1) sealant strain vs. displacement of Mockup C Test 2 Cycle 6.25**

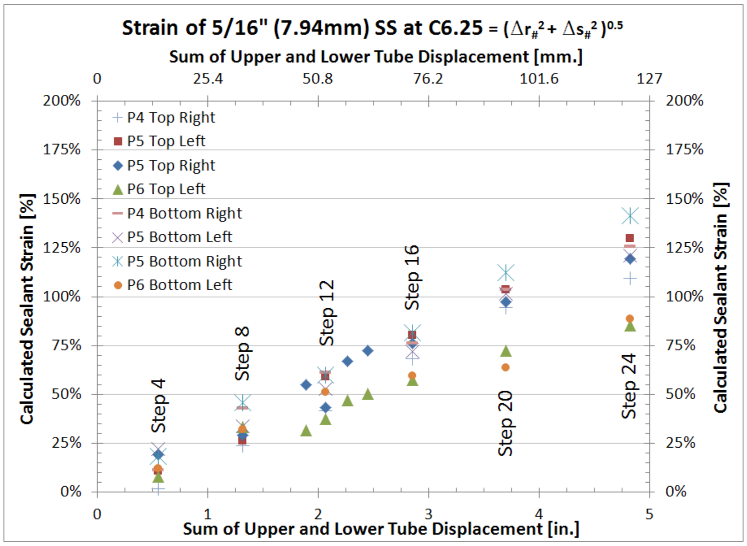


Figure 10 – Calculated (Method 2) strain vs. displacement of Mockup C Test 2 Cycle 6.25

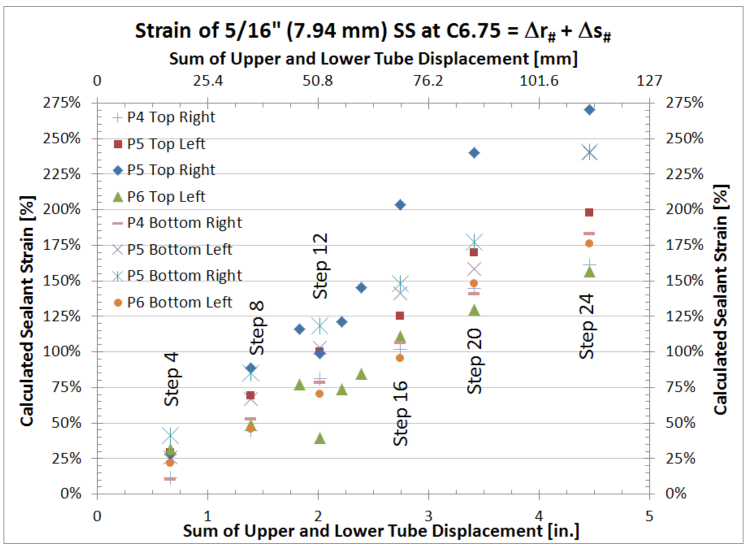


Figure 11 – Calculated (Method 1) strain vs. displacement of Mockup C Test 2 Cycle 6.75

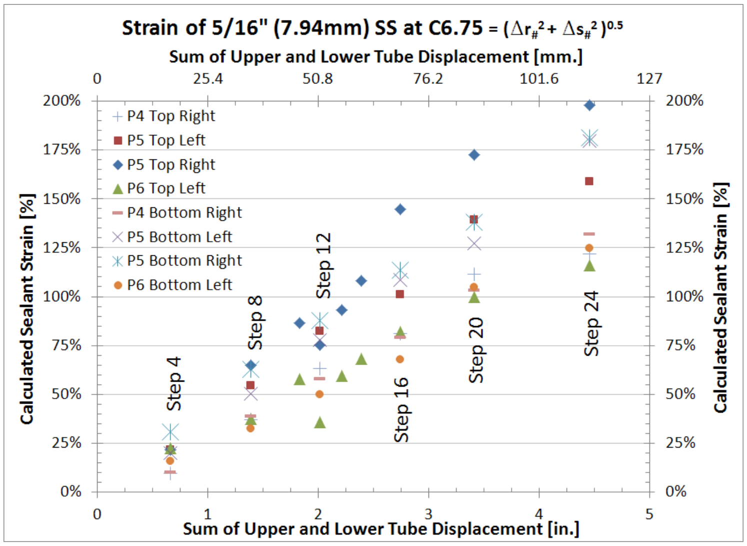


**Figure 12 – Calculated (Method 2) strain vs. displacement of Mockup C Test 2 Cycle 6.75**

The data points shown in Figures 9 to 12 generally show a linear trend and that the calculated strains are greater at a negative drift (C6.75) than at a positive drift of the mockup (C6.25). To quantify this difference, the calculated strains for each step were averaged and plotted (not shown here) to compare the difference between the two cycles. The data points are relatively linear for the steps shown; however a linear regression line has an x-axis-intercept of approximately 1/16" from the C6.25 data and 3/16" from the C6.75 data. This implies that once the mockup reaches an amplitude displacement and returns to its initial displacement of zero, it must then be displaced about +1/16" or -3/16" before the structural sealant returns to an undeformed position. This could be a result of flexibilities in the connection of the mockup to the testing apparatus. In addition, the mockup itself may have some flexibility, which allows for the transoms and mullions to deform without any significant strains of the structural sealant.

## DISCUSSION AND CONCLUSIONS

The video analysis was useful to confirm and document the assumed in-plane movements of the glass relative to the frame during racking. The effective shear strain was calculated from the displacements measured from the video analysis. The accuracy of the technique primarily depends on careful scaling of the images, and the ability to select and follow appropriate tracking points on the mockup. The video capture technique was also useful in determining the rotation of the glass panes and the frame. However, this is not reported here for brevity. The results of this study lead to the following conclusions:

- The linear and quadratic methods of calculating effective shear strain appear to be appropriate approximations, however further study is needed to determine the more appropriate method.
- The drift at which the structural sealant returns to an undeformed state can be approximated following the linear regression line of the maximum deformed strains.

- The drift at which the structural sealant has failed at another corner of the glass pane can be determined by calculating a non-linear decrease in the calculated shear strain from one step to the next.
- The drift at which the structural sealant has failed at a specific corner of a glass pane can be determined by identifying a non-linear increase in the calculated shear strain from one step to the next.

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Simmons, N. 2011. *Analytical Evaluation of Racking Performance of Four-Sided Structural Silicone Glazing Curtain Wall Systems*. MS thesis. The Pennsylvania State University. Web. https://etda.libraries.psu.edu/paper/12618/.

# FINITE ELEMENT MODELING TO PREDICT RACKING TEST RESULTS AND PERFORMANCE OF FOUR-SIDED STRUCTURAL SEALANT GLAZING CURTAIN WALL SYSTEMS

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## ABSTRACT

Full-scale, “unitized”, four-sided structural sealant glazing (4SSG) curtain wall system mockups featuring a re-entrant corner were subjected to cyclic racking displacements in accordance with the American Architectural Manufacturers Association AAMA 501.6 protocol to determine serviceability and ultimate behavior responses. Sealant cohesive failure and glass cracking were identified as limit states and corresponding drift levels were determined. The displacements obtained from the finite element modeling (FEM) were used to calculate the effective shear strain of the structural silicone and the drift capacity of the system. This paper describes the details of the techniques developed for FEM and for the analysis results and shows example application of the method to mockups with racking test results available.

## KEYWORDS

Curtain Wall, Glazing, Dynamic Racking, Finite Element Modeling, Structural Sealant Glazing

## INTRODUCTION

There have been several studies on FEM of glass performance. However, literature review shows few studies have analyzed the racking performance of curtain wall system Memari et al. (2007 and 2011) and Broleen et al. (2012c). In Memari et al. (2007 and 2011) the curtain wall systems were dry-glazed and were modeled using ANSYS software. This paper represents a portion of a recent study presented in detail in Simmons (2011). The objective of the part of the study reported here was to develop FEM technique and analysis of the experimental data in order to calibrate the FEM. In particular, it was of interest to evaluate the translations and rotations of the glass relative to the frame and to analytically determine critical stresses and strains that will lead to sealant failure or glass-to-glass contact.

The FEM technique for this study was developed using SAP2000 software by modeling the mockups from previous studies on comparable four-sided SSG (Memari et al. 2012a), two-sided SSG (Memari et al. 2006), and dry-glazed mockups Memari et al. (2007 and 2011) and comparing the results reported. The developed FEM used mostly linear elastic elements and thus the behavior of the FEM was linear. The mockups of this study were physically tested for three boundary conditions to provide performance features identified or categorized as unitized sway, stick-built-with-vertical-slip, and stick-built. The analytical modeling focus of this study was on the stick-built-with-vertical-slip and stick-built boundary conditions. The results obtained were compared against data recorded from racking tests. The information presented in this paper is useful in developing a better understanding of the behavior of 4SSG curtain wall systems for seismic design. The intent is to avoid a trial and error method of designing a 4SSG curtain wall system. This is significant, since the AAMA 501.6 testing process takes time and consumes resources.

## DISCUSSION OF PHYSICAL TESTING

The physical testing of the mockups was performed as part of a project of which this paper forms a portion of the analytical component. Memari and Kremer (2012c) provide details of the physical testing in a separate report. The following is a description of the constants, variables, observations, and conclusions from that report.

The dynamic racking test facility (Figure 1) used for the experiment consists of two horizontal-siding tubular steel beams, which represented spandrel beams on adjacent stories of a multi-story building. Each specimen was anchored to the sliding tubular beams at the mullions. A hydraulic ram (not shown in Figure 1) drove the bottom beam, while the top beam was coupled to the bottom beam by means of a fulcrum and pivot arm assembly.

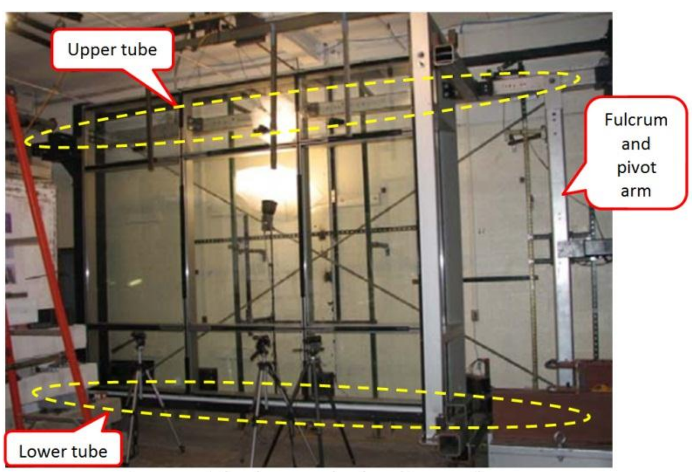


**Figure 1 – Typical Mockup Mounted on the Racking Test Facility**

The testing consisted of three identical mockups (Figure 1). The panels were glazed with Dow Corning 983 Structural Glazing Sealant in 2010. Test data in accordance with AC45 from Dow Corning of the 983 Structural Glazing Sealant indicates an ultimate shear strain limit of approximately 190% to 200%. Mockup A is not reported in this paper. Mockup B was tested with a stick-built boundary condition and mockup C was tested with a stick-built-with-vertical-slip condition. As a result, the behavior of Mockup B was somewhat pure-racking, whereas Mockup C allowed for the panels to slip vertically past each other. The basic dimensions of the mockup are shown in Figures 2 and 3.

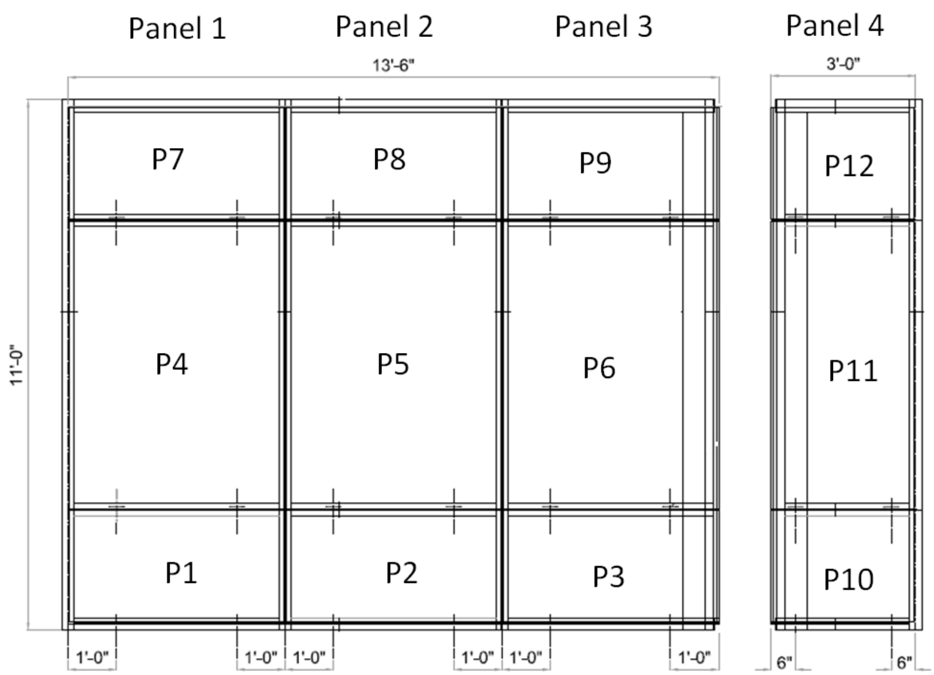


**Figure 2 – Elevation view of three panels and a perpendicular panel of a 4SSG curtain wall system (recreated from drawing provided by Bagatelos Architectural Glass Systems Inc.)**

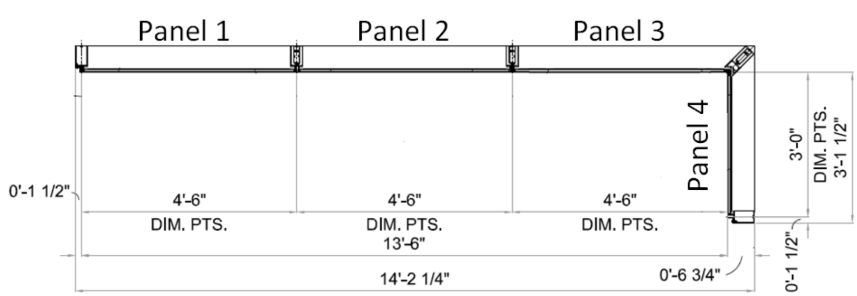


**Figure 3 – Plan view of three panels and a perpendicular panel of a 4SSG curtain wall system (recreated from drawing provided by Bagatelos Architectural Glass Systems Inc.)**

The failure modes of the mockup are defined are similar to those in Memari et al. (2006, 20011 and 2012b). Serviceability failure includes glass cracking or air leakage due to weather-seal and/or structural seal failure. An ultimate failure is when a piece of glass, at least 1 $in^2$ in size, falls out from the mockup. The racking tests followed the procedure outlined in AAMA 501.6 (2009), according to which the racking drift vs. time, is induced in ¼" drift amplitude steps. In this research study, the racking was stopped after each ¼" step for inspection of any structural sealant damage. Figure 4 depicts this drift vs. time for step 12 (maximum nominal amplitude of 3") and highlights the positive and negative amplitudes during the sixth cycle, labeled as C6.25 and C6.75. These are the targeted instants during the test for analysis.

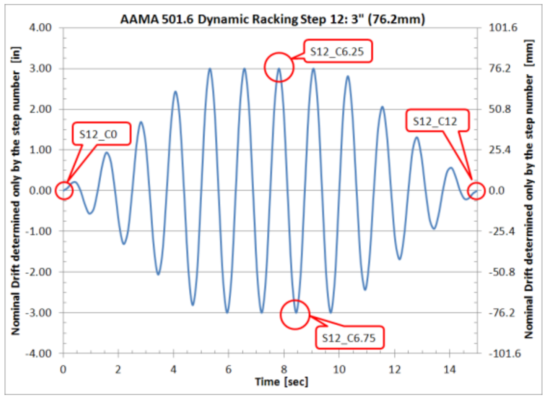


**Figure 4 – Drift vs. Time for Dynamic Racking Step 12 (Modeled after AAMA 501.6 2009)**

## SUMMARY OF FINITE ELEMENT MODEL

The FEM of the 4SSG curtain wall system of this study is composed of transoms and mullions as frame elements, structural sealant as area element type shell-thick, glass as either an area element type shell-thick or as sets of diaphragm constraints applied to the nodes of the structural sealant that are shared with the glass. An effective modulus of elasticity was defined for the structural sealant so that SAP2000 would calculate the correct shear modulus of 71psi. The index clips were modeled as constraints in the X-direction and Y-direction, but not in the Z-direction (vertical) on nodes adjacent to each other on the frame elements for the intermediate mullions.

Simmons (2011) discusses in detail the determinations of material input values and selection of element types to be assigned in the FEM. These values and types are summarized in Tables 1 to 3. Many of the values shown for the aluminum material were the default values set by SAP2000. The dimensions of the elements were determined by the design drawings of the mockup or from measurements of the physical mockup.

**Table 1 – Materials Properties in the FEM**

| Properties | Aluminum | Glass | Structural Silicone |
|---|---|---|---|
| Material Type | Aluminum | Other | Other |
| Modulus of Elasticity, E [ksi] | 10,000 | 1,050 | 0.212 |
| Poisson ratio, $\upsilon$ | 0.33 | 0.25 | 0.495 |
| Shear Modulus, G [ksi] | 3,762 | 418 | 0.071 |
| Aluminum Type | Wrought | | |
| Aluminum Alloy Designation | 6061-T6 | | |
| Compressive Yield Strength, $F_{cy}$ [ksi] | 35 | | |
| Tensile Yield Strength, $F_{ty}$ [ksi] | 35 | | |
| Tensile Ultimate Strength, $F_{tu}$ [ksi] | 38 | | |
| Shear Ultimate Strength, $F_{su}$ | 24 | | |

**Table 2 – Properties assigned to the FEM frame elements**

| Properties | Edge Mullion | Split Mullion | Transom |
|---|---|---|---|
| Frame Section Type | Tube | Tube | Tube |
| Material | Aluminum | Aluminum | Aluminum |
| Outside depth ($t_3$) [in.] | 3 | 1 | 3 |
| Outside width ($t_2$) [in.] | 5.1875 | 5.1875 | 5.5 |
| Flange thickness ($t_f$) [in.] | 0.125 | 0.125 | 0.125 |
| Web thickness ($t_f$) [in.] | 0.1875 | 0.1875 | 0.125 |
| Property modifiers | none | None | none |

**Table 3 – Properties assigned to the FEM shell elements**

| Properties | Structural sealant along transoms | Structural sealant along mullions | Glass |
|---|---|---|---|
| Element type | Shell-thick | Shell-thick | Shell-thick |
| Material Angle | 0 | 0 | 0 |
| Membrane thickness [in.] | 0.5625 | 0.5625 | 0.5 |
| Bending thickness [in.] | 0.5625 | 0.5625 | 0.5 |
| **Property Modifiers** | | | |
| Membrane f12 | 0.9091 | 0.9091 | 1 |
| Shear v13 | 1 | 1.2 | 1 |
| Shear v23 | 1.2 | 1 | 1 |
| All other modifiers | 1 | 1 | 1 |

The 4SSG curtain wall system of this research poses a modeling issue with the intermediate transom. Figure 5 shows the horizontal detail of the mockups which includes the intermediate transom. Each intermediate transom has two strips of structural sealant attached it, in which one strip is for an upper glass pane and the other is for a lower glass pane. Thus the representation of the transom must interface with two strips of area elements without the area elements interacting with each other directly. This issue does not occur with the mullion, because the intermediate stack joint is a split-mullion design. A representation of the FEM is shown in Figure 6 where the area elements for the two strips of structural sealant are drawn so that they are connected at the same node of the frame element, but on opposite sides so that the nodes connected to the glass elements do not overlap.

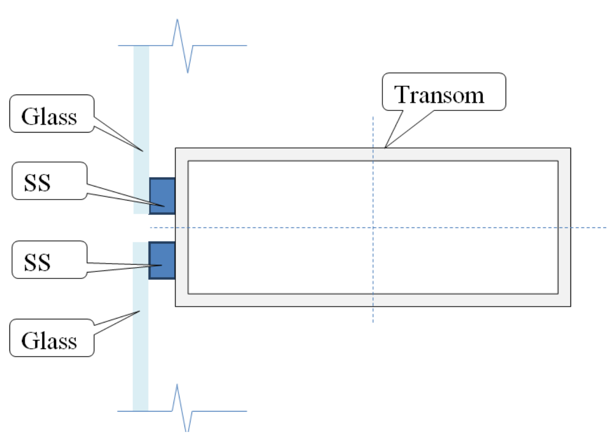


**Figure 5 – Realistic detail of the glass-silicone-transom interface at the intermediate transom**

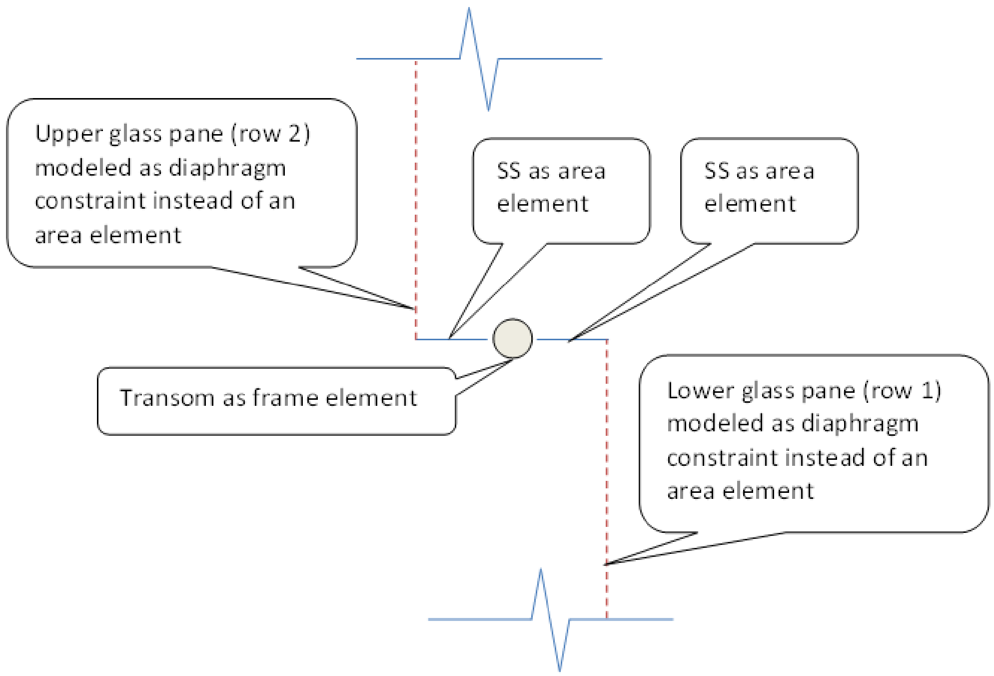


**Figure 6 – FEM Representation of the glass-silicone-transom interface at the intermediate transom**

## FEM COMPARED TO HYSTERESIS DATA FOR LOAD VS. DISPLACEMENT RESULTS

The objective of comparing the load vs. displacement data is to verify the accuracy of the FEM before studying the shear effect of the strains on the structural sealant. It is assumed that the stiffness accuracy is related to the structural sealant strain accuracy.

### Stick-built boundary condition (MB_T2)

The hysteresis data for the stick-built boundary condition show a change in the behavior of stiffness after step 13; this is due to plastic deformation of the mockup and after step 16 the behavior changes again due to failure of the structural sealant (rupture / tearing). Since the FEM uses linear material properties for the structural sealant it is only expected to be accurate prior to the failure of the structural sealant. The following comparisons are from the step 12, which equated to an inter-story drift of 1.95" for C6.25 and -1.99" for C6.75, because structural sealant failure was not noted until step 16. Figure 7 shows a plot of both the FEM and physical test results for both MB_T2 and MC_T2. The x-axis of Figure 7 represents an inter-story drift.

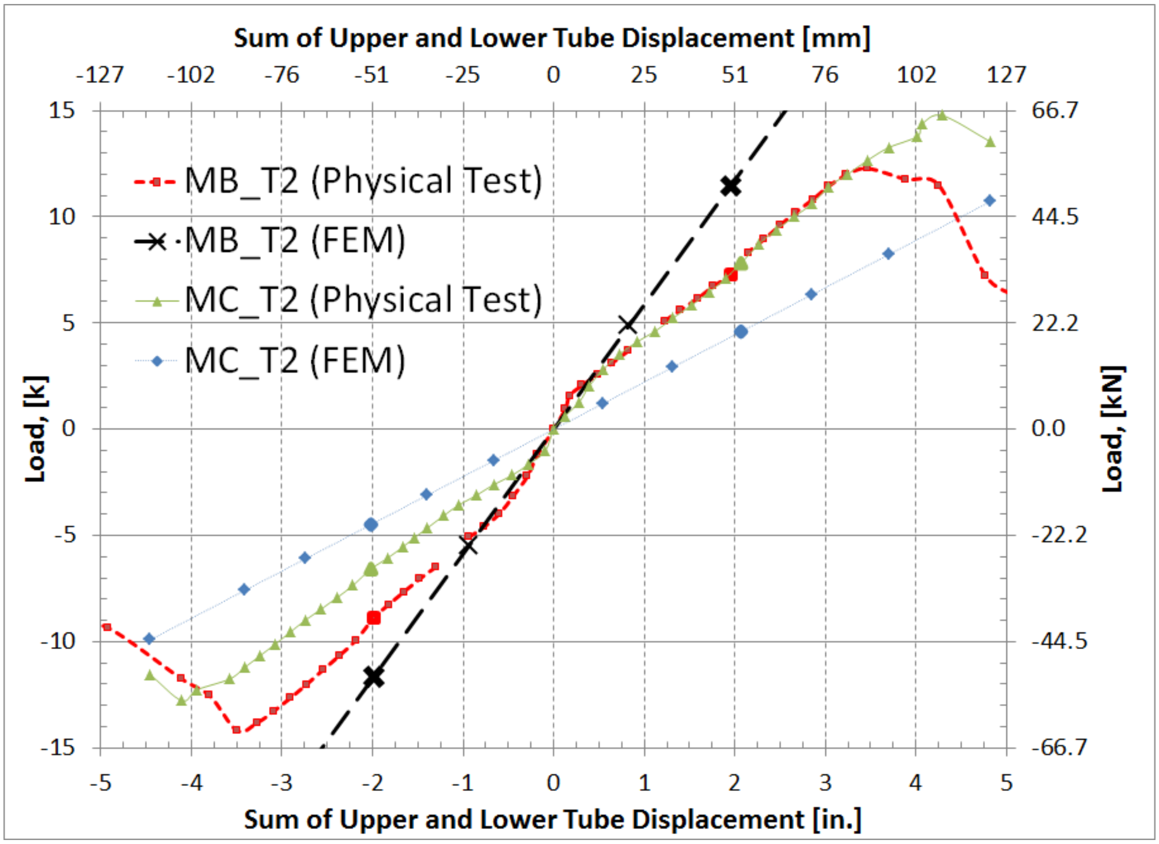


**Figure 7 – Comparison of physical test data of MB_T2 and MC_T2 with the FEM results**

The FEM results shown in Figure 7 approximate the response as linear, and this matches the physical data at small drifts very well. The FEM predicted a force (10.74k and -10.95k) 48% and 23% larger than what was recorded during the physical testing of the mockup (7.28k and -8.88k) respectively for drifts 1.95" and -1.99". Although the differences seem large, they are good approximations considering that the SAP2000 FEM uses linear material properties for the structural sealant, static loading, and no plastic deformation of any of the materials is considered. The SAP2000 FEM also does not account for drops in stiffness of any of the materials due to fatigue or failure of the materials.

**Stick-built-with-vertical-slip boundary condition (MC_T2)**

The behavior of MC_T2 is shown in Figure 7 to remain linear at higher drifts than that of MB_T2. The observed structural sealant damage to MC_T2 was minimal. In a separate part of the study, a video analysis showed that the structural sealant strain of MC_T2 was more linear than that of MB_T2. Thus comparisons between the hysteresis load vs. displacement data and the FEM is not limited to Steps 1 through 12 like it is for MB_T2. However, comparison will be made for the results of step 12, so that comparisons can also be clearly made between MB_T2 and MC_T2. Step 12 equates to a displacements of 2.07" for C6.25 and -2.02" for C6.75 for MC_T2.

The physical data of MB_T2 and MC_T2 are similar in the positive direction and are slightly offset in the negative direction (Figure 7). The cause of this difference between

MB_T2 and MC_T2 is unknown, but one explanation is due to the compression and tension interaction and/or plastic deformation of the index clips at the re-entrant corner. Another possible cause could be the plastic deformation of the channel at the re-entrant corner. It is believed that the vertical slip boundary condition allows more load to be transferred to the index clips and the channel leading to plastic deformation. It is recommended for future FEM studies that these elements be systematically modeled as MultiLinear Plastic links using trial values for the material properties and the load case type must be changed from Static to Multi-step Static.

The FEM predicted reaction forces (4.60k and -4.49k) 41% and 32% smaller than what was recorded during the physical testing of the mockup (7.81k and -6.58k) respectively for drifts 2.07" and -2.02". Although the differences seem large, they are good approximations considering that the SAP2000 FEM is using linear material properties for the structural sealant and static loading. The SAP2000 FEM also does not account for drops in stiffness of any of the materials due to fatigue or failure of the materials.

## EFFECTIVE SHEAR STRAIN OF STRUCTURAL SEALANT (MB_T2)

A technique was used to measure the movement of the glass corners relative to the mullions and transoms which is the same as the deformation of the structural sealant. The FEM calculated the displacement of nodes, which directly correlated to the longitudinal shear (Δr) and transverse shear (Δs) of the structural sealant. These values are used to calculate the effective shear (Δt) based on two methods. The first method is a linear relationship of longitudinal shear plus transverse shear. $\Delta t = |\Delta r| + |\Delta s|$. The second method is a quadratic relationship of the square root of the sum of longitudinal shear squared plus transverse shear squared. $\Delta t = \sqrt{\Delta r^2 + \Delta s^2}$.

The displacement of the nodes were recorded from the FEM analysis and used to determine the horizontal and vertical deformation components of the structural sealant at glass pane corners. Then the effective shear strain was calculated by two methods. These results are presented in Table 4. The calculated effective shear stains from a video analysis presented in Simmons (2011) is shown in Table 5 for comparison.

**Table 4 – Movement of glass corners relative to frame, determined from FEM of MB_T2_S12_6.75**

| | Horizontal Displacement [in.] | Vertical Displacement [in.] | Method 1 Linear Strain [%] | Method 2 SQRT Strain [%] |
|---|---|---|---|---|
| P5 Top Left | 0.29 | -0.29 | 185% | 131% |
| P5 Top Right | 0.29 | 0.29 | 185% | 131% |
| P6 Top Left | 0.29 | -0.30 | 188% | 133% |
| P5 Bottom Left | -0.28 | -0.29 | 181% | 128% |
| P5 Bottom Right | -0.28 | 0.29 | 181% | 128% |
| P6 Bottom Left | -0.27 | -0.27 | 175% | 124% |

**Table 5 – Movement of glass corners relative to frame of MB_T2_S12_6.75 (Simmons 2011)**

| | Horizontal Displacement [in.] | Vertical Displacement [in.] | Method 1 Linear Strain [%] | Method 2 SQRT Strain [%] |
|---|---|---|---|---|
| P5 Top Left | 0.11 | -0.30 | 133% | 104% |
| P5 Top Right | 0.10 | 0.21 | 100% | 75% |
| P6 Top Left | 0.02 | -0.14 | 52% | 45% |
| P5 Bottom Left | -0.05 | -0.22 | 87% | 73% |
| P5 Bottom Right | -0.11 | 0.14 | 82% | 59% |
| P6 Bottom Left | -0.20 | -0.12 | 103% | 74% |

These values from the FEM (Table 4) are very consistent for each of the six locations. This also indicates that the FEM is relatively symmetric and is not significantly influenced by the perpendicular panel or the channel. However, the values from the video analysis (Table 5) show some significant variances among the six locations. Unfortunately, the average differences of 349% for the horizontal direction and 66% for the vertical direction of the FEM results from the video analysis are quite large. The majority of this variance is most likely caused by the FEM's lack of non-linear representation of the plastic deformation of the frame and channel at higher drifts or the failure of the structural sealant before a shear strain of 200% due to workmanship. MultiLinear Plastic elements could be used to model the non-linear behavior. The input values for the MultiLinear Plastic element may need to be determined by trials of modeling and comparing the results of a mockup with a unitized sway boundary condition. Another possible source for the variance between the FEM and the physical results is that the behavior of structural sealant was verified based on a 2" long coupon test rather than a significantly longer strip of structural sealant, which might better represent the structural sealant along a single edge of a glass pane. A small portion of the variance is most likely caused by the human error resulting from selecting the correct frame from the video, scaling and rotating the image, and measuring it.

## MEASUREMENT OF GLASS PANE ROTATIONS (MB_T2)

Table 6 shows the measured values of the rotations of glass panes from the FEM of the mockup with the stick-built boundary condition and applied displacement of 1.99" in the C6.75 direction. These rotations were very similar to values calculated from a video analysis reported in Simmons (2011). Knowing the amount of rotation per applied drift can be useful in developing kinematic equations for approximating the drifts at which structural sealant fails or glass-to-glass contact occurs, as is discussed in Simmons (2011). The FEM was able to make reasonable predictions for the drift at which glass-to-glass contact occurs. MB_T2 did have glass-to-glass contact however this occurred after structural sealant failure and non-linear behavior.

**Table 6 – Summary of rotations of the glass determined from FEM of MB_T2_S12_6.75**

| Rotation of glass panes [rad] | | | Average of each row |
|---|---|---|---|
| P7 = -0.00543 | P8 = -0.00455 | P9 = -0.00722 | -0.00573 |
| P4 = -0.01263 | P5 = -0.01210 | P6 = -0.01250 | -0.01241 |
| P1 = -0.00475 | P2 = -0.00362 | P3 = -0.00313 | -0.00383 |

## DISCUSSION AND CONCLUSIONS

The stiffness recorded from the physical testing at lower steps was similar to the FEM results. At higher steps the physical mockup showed non-linear behavior. The FEM did not effectively incorporate plastic deformation of the aluminum frame or the steel channel of the lower sliding tube to achieve this non-linear behavior, and can be considered a linear approximate of the actual nonlinear response. The movement of the glass pane corners relative to the aluminum frame corners differed considerably between the FEM and the physical mockup. The results of this study show that the FEM can:

- Approximate the stiffness of curtain wall system using linear elements.
- Approximate the displacements of the glass, relative to the frame, so that these values may calculate the effective shear strain.
- Approximate the drift at which glass panes make contact with each other.

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# EFFECTS OF BOLT SPACING ON PRYING FORCES IN WT CONNECTIONS

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## ABSTRACT

WT connections are commonly used within the structural steel frame. These connections may be used as a hanger connection or as a flange connection element in a moment connection. When the flange of a WT shape is bolted to a column or a beam and the WT stem is subjected to a tensile loading, the tensile force in the bolts can increase due to prying action. Although prying action in tees is a well-studied phenomenon, current design provisions do not directly address how increasing bolt spacing parallel to the WT stem impacts prying force.

This experimental study focuses on the effects of changing bolt spacing parallel to the stem when the tee is subjected to a tensile force. A total of ten tests were conducted considering WT specimens with two different flange thicknesses and five different spacing between the bolts. Bolt forces, determined from strain measurements, were compared to the applied tensile force to determine the magnitude of prying force. Displacement measurements were also taken and deformation demand was quantified and correlated to prying force.

Experimental tests show that bolt spacing parallel to the WT stem affects prying force in the bolts. As bolt spacing increases, prying force decreases. As would be expected, WT flange thickness affects deformation and plays a role in the magnitude of the prying force. Trends regarding bolt spacing are consistent when comparing the WT specimens with different flange thicknesses.

## INTRODUCTION

WT shapes are used in a variety of steel connections. Common applications for WT shapes are beam-to-column shear and moment connections, diagonal brace connections and hanger connections. When the flanges of a WT are bolted to a column, beam, or base plate and the web is pulled in tension, bolt force is increased due to prying action.

The flange thickness of the WT is a critical piece of the prying action analysis. If the flange is sufficiently stiff, flange deformation will be minimal and prying forces will be negligible. If the flange lacks sufficient stiffness, the bolt may accrue significant prying forces. Possible limit states include fracturing of the bolts and/or web of the WT shape and flange deformation failure (Swanson and Leon 2000).

Studies such as Nair et al. (1969), Nair et al. (1974), Zoetemeijer (1974), Thornton (1985), Wheeler et al. (1998), Swanson and Gao (2000), Swanson and Leon (2001), Swanson (2002), Willibald et al. (2002) and Dowswell (2011) have described how to calculate and predict the resulting prying forces, and many of those studies have led to the current design provisions (AISC 2011).

## AISC DESIGN PROVISIONS

The Steel Construction Manual (AISC 2011) includes provisions for prying action. The minimum flange thickness, $t_{min}$, for prying forces to be considered negligible is

$$t_{min} = \sqrt{\frac{4Tb'}{\phi p F_u}},$$

where $T$ is the required strength per bolt in kips, $b'$ is the location of maximum bending moment relative to the bolt hole, $\phi$ is the reduction factor and $F_u$ is the tensile strength of the steel. The tributary length, $p$, is limited by using the maximum of $2b$ and the bolt spacing, $s$, where $b$ is the distance from web face to bolt center (AISC 2011). These parameters are illustrated in Figure 1.

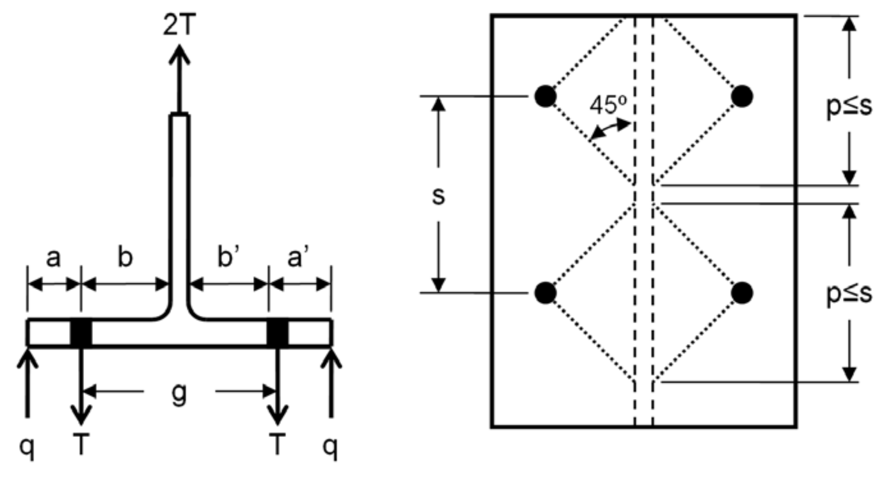



**Figure 1: (a) Cross Section Showing Forces & Variables; (b) Plan View Showing Spacing Variables.**

If it is determined $t < t_{min}$ then prying forces must be considered. The prying force, $q$, is calculated as

$$q = B\left[\delta\alpha\rho\left(\frac{t}{t_c}\right)^2\right],$$

where

$$t_C = \sqrt{\frac{4Bb'}{\phi p F_u}},$$

$$\delta = 1 - \frac{d'}{p},$$

and

$$\alpha = \frac{1}{\delta}\left[\frac{T}{B}\left(\frac{t_c}{t}\right)^2 - 1\right].$$

In the equations above, $B$ is the available tension per bolt and $d'$ is the width of the hole along the length of the tee. The flange thickness, $t_c$, is the minimum required to develop the required design tensile strength of the bolts without prying action (AISC 2011). According to the AISC provisions, the ratio of the moment at the bolt line to the moment at the face of the tee stem, $\alpha$, shall be greater than zero but less than or equal to one; however some studies (Swanson 2002) using $\alpha$ greater than one have been conducted. When $\alpha$ is equal to zero, no moments are generated within the flange resulting in no prying forces. When $\alpha$ is equal to one, prying force is assumed to be at its maximum. The resulting total bolt force is the sum of the applied load plus the prying force.

## OBJECTIVE

Studies by Zoetemeijer (1974), Thornton and Kane (1999), Swanson (2002) and Dowswell (2011) have indicated that bolt spacing has some effect on the prying force. The objective of the current research initiative is to better understand the effect bolt spacing has on prying forces in a WT connection, with the hypothesis that prying force will diminish as bolt spacing parallel to the tee stem increases. The prying forces measured will be compared to calculations using the provisions from AISC (2011).

As was mentioned previously, the provisions from AISC limit $\alpha$ to one. Although not the primary focus of this paper, cases where $\alpha$ is greater than one will be considered.

## EXPERIMENTAL PROGRAM

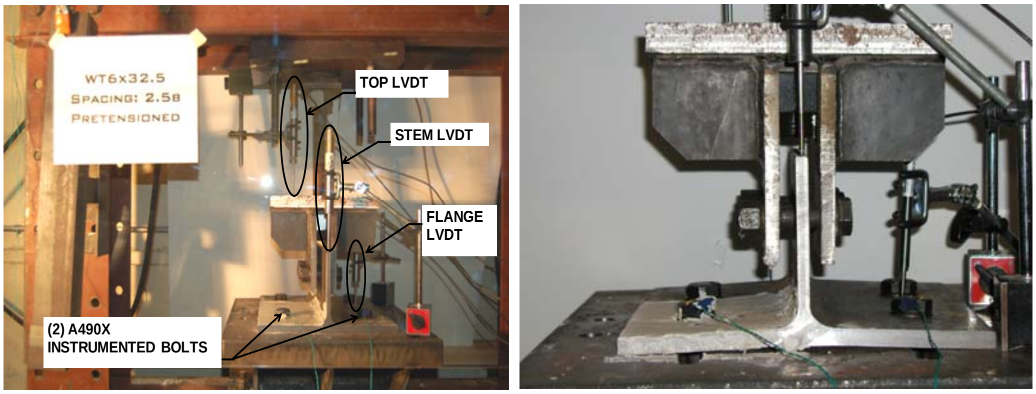
Two WT sizes were selected; a WT6×32.5, in which the flange thickness is somewhat less than the minimum required to neglect prying forces, and a WT6×43.5, which is just slightly thinner than the minimum thickness required to neglect prying forces. As such, it was expected that prying forces in the bolts would be lower for the WT6×43.5 specimens than for the WT6×32.5 specimens.

The test setup used is illustrated in Figure 2(a). The WT is bolted to a very stiff base plate, which is connected to a self-reacting test frame. The stem of the WT is bolted to an assembly that will apply tensile loading on the stem by means of a hydraulic actuator. Two of the four bolts connecting the WT to the base plate are instrumented with inner-bolt strain gages which are used to measure strain in the bolts at the flange connection, which is then used to calculate bolt force. Displacements are measured at three locations: at the top of the assembly applying force in order to measure total displacement (labeled "top LVDT" in Figure 2), at the top of the stem of the WT between bolts in order to measure flange displacement within the cross-section (labeled "stem LVDT"), and at the midpoint between the bolts attaching the WT to the base plate, in order to measure flange displacement parallel to the tee stem (labeled "flange LVDT"). Applied load, corresponding to the force "2T" in Figure 1, was measured by means of a load cell, not shown in Figure 2, with a 100 kip capacity. An example of a typical deformed shape for a WT6×32.5 specimen at a 100 kip applied load is shown in Figure 2(b).

Since AISC (2011) limits the spacing of the bolts to twice the distance from the centerline of the bolt hole to the face of the tee stem (i.e., 2.0*b*), it was decided that the bolt spacing would be varied by a factor of that distance. Thus, five different spacings were considered: 1.5*b*, 2.0*b*, 2.5*b*, 3.0*b* and 4.0*b*.

The flange bolts were minimally pre-tensioned to ensure constant contact between the flange of the WT specimen and the base plate throughout load application. The instrumented bolts were tightened until the strain measured approximately 300 to 350 microstrain, corresponding to approximately 3.8 to 4.4 kips. Since two of the four bolts in each experiment were not instrumented, the non-instrumented bolts were tightened approximately the same amount as the instrumented bolts as judged by the effort required to tighten the bolts.

The load was applied slowly and consistently. When the applied load measured approximately 10 kips, the load was held briefly to confirm that all instruments were reading properly. From that point, the applied load was increased until a magnitude of 100 kips was reached (the limit of the load cell's capability).




**(a)** **(b)**

**Figure 2: Typical Test Setup (a) Before Loading and (b) at 100 kip Loading (WT6×32.5 shown).**

## EXPERIMENTAL RESULTS

As mentioned previously, Figure 2(b) shows a typical deformed shape for a WT6×32.5 specimen under a 100 kip applied load. The picture shows the distortion between the bolts and the contact between the base plate and the edges of the WT flange. This deformed shape agrees with the force diagram shown in Figure 1 indicating that prying forces are present in the bolts.

*WT6×32.5 at Bolt Spacing 1.5b*

The WT6×32.5 at a bolt spacing of 1.5*b* will be discussed in detail. Results from all other specimens will be compared. Complete details for all specimens are found in DeSimone (2012) and Meier (2012).

Figure 3 shows a plot of applied load versus displacement. The applied load engaged (i.e., removed slack within) the test frame within the range between zero and approximately 5 kips of applied load. Once engaged and applying load to the specimen, a linear trend occurred as load was applied indicating elastic behavior until the point of the "transition zone." The transition zone is the point where plastic hinging occurs within the flange. The nonlinear trend beyond the transition zone shows a degradation of stiffness in the specimen, and one can see that the applied load accrual is approaching zero at the end of the trace. Testing was ended when the applied load reached 100 kips due to the limitation of the load cell.

Figure 4 shows a plot of applied load per bolt versus measured bolt force, and Figure 5 shows a plot of applied load per bolt versus prying force. Assuming equal force distribution between bolts, the prying force was found by subtracting the total applied load from the sum of the bolt forces and dividing by the number of bolts. Once again, the system initially engaged the test frame. Once engaged, a linear trend occurred as load was applied indicating elastic behavior until the point of the "transition zone." The plastic hinging occurs within the flange and the prying forces in the bolts increased more rapidly beyond the transition zone. One can see the applied load accrual approach zero at the end of the plot in Figure 5, agreeing with the similar observation noted for Figure 3.

Figure 6 shows the relationship between bolt force versus prying force, further illustrating the point that prying force gathers at a faster rate once a plastic hinge has developed in the flange of the tee.

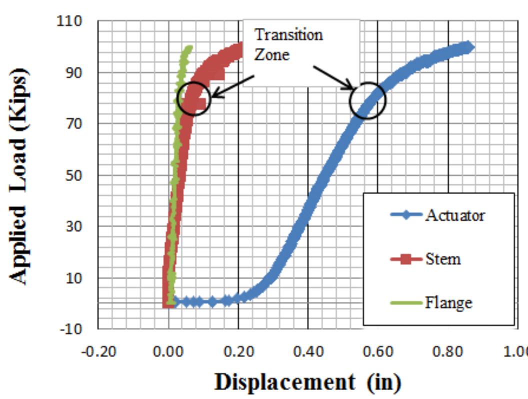



**Figure 3: Applied Load versus Displacement for WT6×32.5 Specimen with 1.5*b* Spacing.**

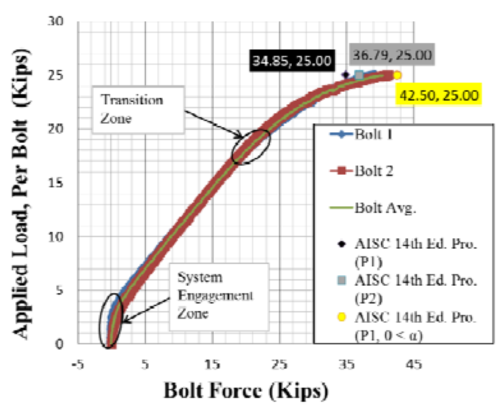



**Figure 4: Applied Load versus Bolt Force for WT6×32.5 Specimen with 1.5*b* Spacing.**

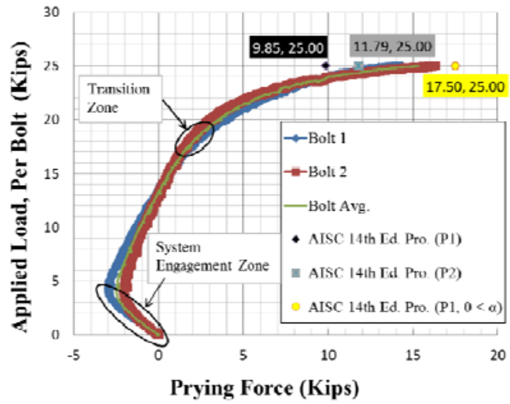



**Figure 5: Applied Load versus Prying Force for WT6×32.5 Specimen with 1.5*b* Spacing.**

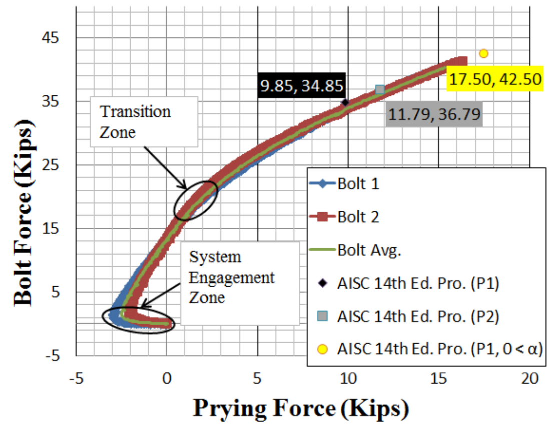



**Figure 6: Bolt Force versus Prying Force for WT6×32.5 Specimen with 1.5*b* Spacing.**

AISC provisions limit the tributary length, *p*, as indicated in Figure 1(b). This is represented as P1 in Figures 4, 5 and 6. For comparison, the actual tributary length was also plotted and is represented as P2 in the plots. Figures 7 and 8 show the results of the effective length, also known as the tributary length in AISC, versus bolt force and the bolt force versus *α*, respectively. The effective length increases linearly with the increasing bolt force until the flange begins to yield. When the flange has fully yielded, the effective length begins to decrease. The effective length is the length at which the moment in the flange is being distributed; therefore, a larger effective length results in a wider distribution of moment.

When comparing Figures 7 and 8, a noticeable transition zone occurs at approximately 20 kips of bolt force. The effective length peaks at approximately 25 kips of bolt force corresponding to an effective length of approximately 8.5 in. However, the maximum effective length does not occur at the maximum bolt and prying forces. The value of *α* is nonlinear beyond 25 kips of bolt force. Based on this and prior figures, plastic hinges have developed in the flange at this point. The experimental value for alpha is at a maximum and is approaching its peak when the experiment is concluded at 100 kips of applied load. The resulting maximum average bolt force was measured at 41.383 kips and an average maximum value for alpha of 1.398 was calculated.

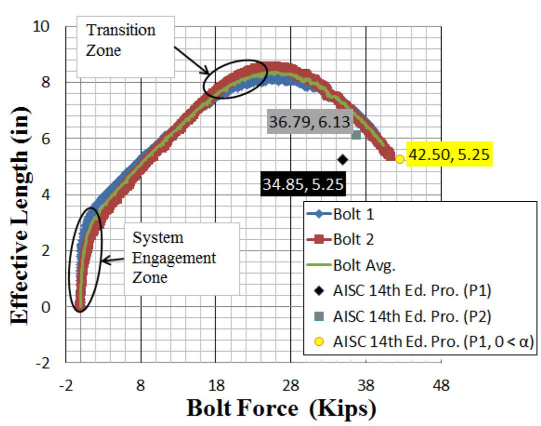



**Figure 7. Effective Length versus Bolt Force.**

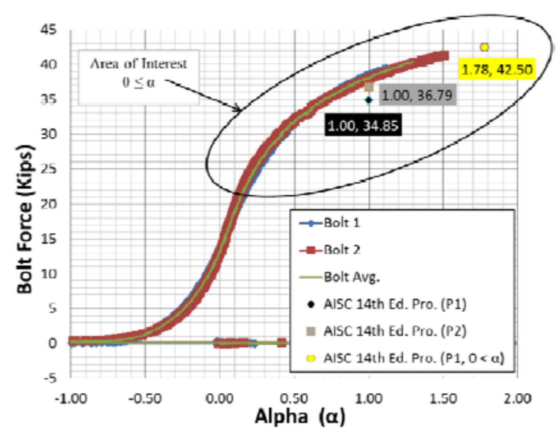



**Figure 8. Bolt Force versus Alpha.**

*Results Comparisons for all Specimens*

Figure 9 shows comparisons between the five WT6×32.5 specimens tested. The figure shows that, for a given applied load, bolt force decreases as bolt spacing increases. The comparison shown on the plot is based on a 100 kip applied load (25 kips per bolt).

When comparing bolt force to prying force, Figure 10 indicates a consistent drop in prying force as the bolt spacing was increased. Figure 10(a) shows results from the W6×32.5 specimens and Figure 10(b) shows results from the W6×43.5 specimens. Results from each of the tests approach the "limit line" as shown in the figure.

Table 1 shows the maximum experimental bolt force and prying force for all specimens. When taking into account the engagement zone of the system, a value for the total prying force can be determined. A value denoted as $q_{offset}$ takes the engagement force into consideration, effectively adding to the maximum prying force. Thus, the total prying force in each bolt is the absolute range from the applied load versus prying force plots. Table 1 shows that prying force decreases as bolt spacing increases, thus agreeing with the observations from Figures 9 and 10. The reader should note that the W6×43.5 specimen with the 2.0*b* spacing experienced an error during testing, resulting in imbalanced loading. As such, bolt forces were inconsistently applied, resulting in inconsistent prying forces. This specimen was excluded from the comparison.

The results produced confirm the hypothesis that as the bolt spacing is increased parallel to the stem the prying force decreases. Furthermore, the data suggests that provisions could be developed to take advantage of the reduction in prying force at lengths exceeding 2.0*b*. Developing new or enhanced design provisions was beyond the scope of this research initiative, and the authors recognize that too few specimens were tested to propose new provisions. However, the results of these experiments show that enhancements to existing provisions may be warranted.

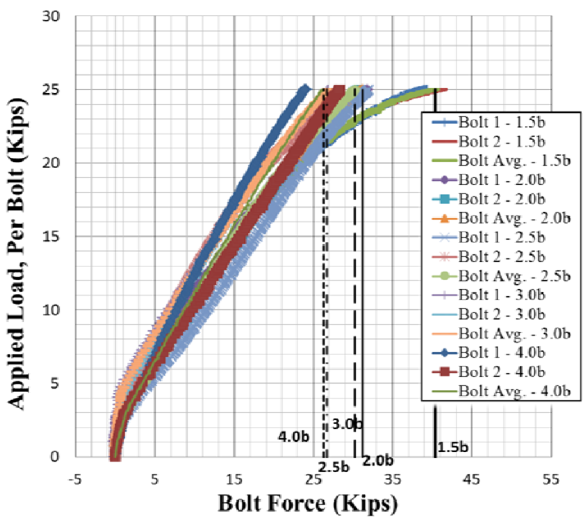
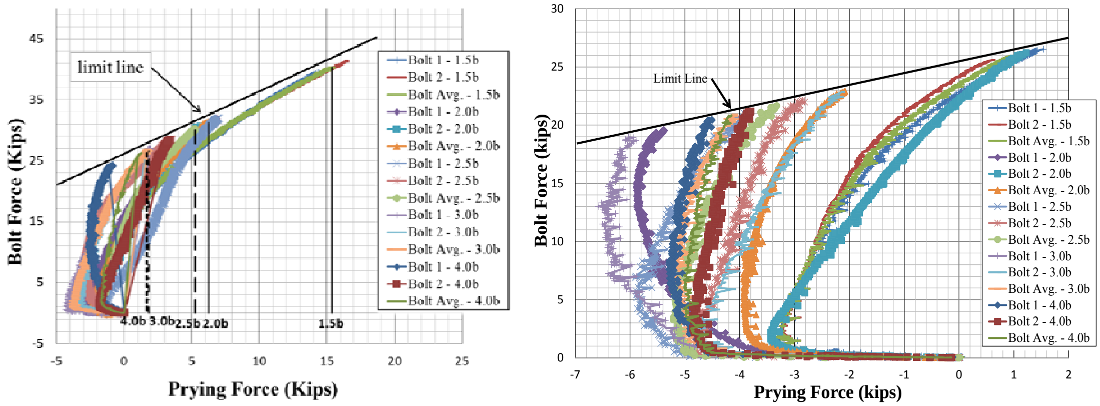



**Figure 9: Applied Load Per Bolt versus Prying Force for All WT6×32.5 Specimens.**




**(a)** **(b)**

**Figure 10: Bolt Force versus Prying Force for (a) WT6×32.5 and (b) WT6×43.5 Specimens.**

| Experimental Results Summary for All WT6x32.5 Specimens | | | | | | | |
|---|---|---|---|---|---|---|---|
| Specimen | Avg. Pre-Tension Force (kips) | Avg. Max Bolt Force (kips) | Avg. $q_{max}$ (kips) | Net Prying Force Difference (kips) | Avg. $p_{max}$ (in.) | Displacements (in.) | |
| | | | | | | Stem | Flange |
| 1.5b | 4.37 | 40.34 | 15.36 | 18.36 | 8.38 | 0.239 | 0.067 |
| 2.0b | 4.70 | 31.24 | 6.25 | 8.5 | 9.74 | 0.176 | 0.202 |
| 2.5b | 4.40 | 30.22 | 5.23 | 6.98 | 9.98 | 0.122 | 0.136 |
| 3.0b | 5.25 | 26.74 | 1.83 | 5.33 | 11.44 | 0.142 | 0.210 |
| 4.0b | 4.65 | 26.27 | 1.7 | 3.20 | 11.73 | 0.126 | 0.258 |

| Experimental Results Summary for All WT6x43.5 Specimens | | | | | | | |
|---|---|---|---|---|---|---|---|
| Specimen | Avg. Pre-Tension Force (kips) | Avg. Max Bolt Force (kips) | Avg. $q_{max}$ (kips) | Net Prying Force Difference (kips) | Avg. $p_{max}$ (in.) | Displacements (in.) | |
| | | | | | | Stem | Flange |
| 1.5b | 4.20 | 26.06 | 1.07 | 4.35 | 7.09 | 0.059 | 0.038 |
| 2.0b | 4.24 | 22.91 | 0.56 | *1.75 | 7.86 | 0.046 | 0.02 |
| 2.5b | 4.95 | 21.66 | 0.015 | 1.85 | 8.17 | 0.076 | 0.015 |
| 3.0b | 4.56 | 20.90 | -0.11 | 1.10 | 8.35 | 0.02 | 0.018 |
| 4.0b | 4.90 | 20.84 | -0.12 | 0.80 | 8.38 | 0.086 | 0.046 |

* Net prying force difference had lower value versus next larger spacing due to imbalanced specimen loading.

**Table 1: Experimental Results Summary for All Specimens.**

Figure 11 shows the experimental results versus the AISC (2011) provisions. Specimen 1.5*b* shows some additional interest with the possibility of alpha greater than one, and specimen 2.0*b* is the bolt spacing at which AISC limits the prying force calculations.

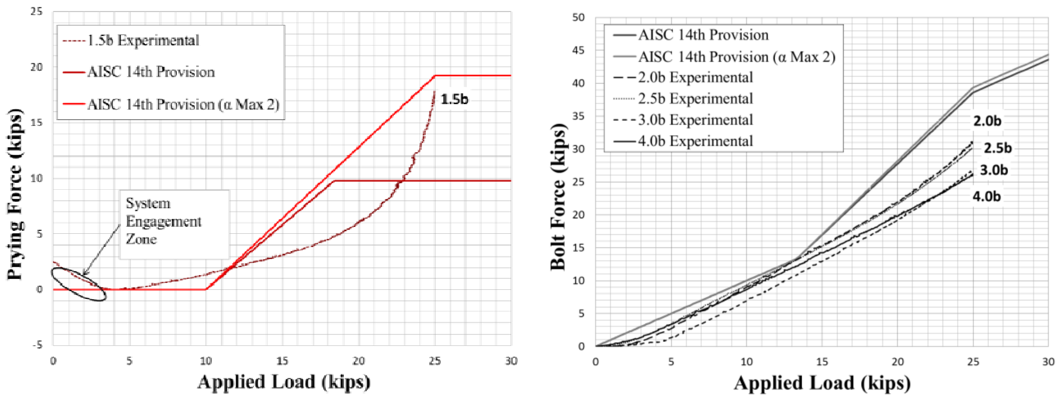



**Figure 11. Bolt Force versus Applied Load as Compared to AISC (2011) Provisions.**

The correlation between experimental results and the AISC provisions is very good at low levels of applied load (less than 15 kips per bolt). As applied load per bolt increases the experimental and AISC provisions separate somewhat, showing a slight overestimation of bolt force by AISC. The traces begin to come together again as the prying force influences the total bolt force, with the 1.5*b* specimen nearly intersecting the AISC trace at the level of maximum bolt force.

## CONCLUSIONS

This paper presented results from experimental testing of WT hanger-type connections. Several different bolt spacings parallel to the stem of the WT were considered in order to gain insight into the effect of bolt spacing on prying force in the flange bolts.

Based on the results presented, it is concluded that prying force magnitudes decrease as the bolt spacing parallel to the tee stem increases. The decrease in prying force is directly related to the effective length experienced within the flange, which reaches a maximum as the flange yields.

A decrease in prying force may be realized as spacing exceeds 2.0*b*. However, additional studies are necessary to develop an appropriate design provision for use when spacing exceeds that which is currently allowed in the AISC provisions.

Based on the results presented for specimens with bolt spacing less than that of the AISC (2011) limitations, the actual value for alpha should be used since it compares well with the experimental results. For specimens beyond the AISC limitations, an increase of effective length may be considered since the experimental results show the possibility for utilizing a larger effective length than currently permitted by AISC provisions.

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# THE IMPERMANENCE OF PERMANENCE: QUESTIONING PERMANENCE AS A CENTRAL TENANT OF SUSTAINABILITY

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## ABSTRACT

For architects, the aspiration to leave a legacy manifests itself through the creation of long-standing structures. As such, permanence is a central proponent of many definitions of sustainability, including those of architect William McDonough and the Congress for New Urbanism. There are, however, issues with thinking in terms of these "permanent" solutions. The fast-pace of technological advances coupled with the desire to rush new technology to implementation engenders two of the main issues with permanence. First, the lifespan of a building often far outlasts the relevancy of its performative systems, and second, new sustainable strategies are frequently implemented before their effectiveness can be quantified. Impermanent thinking – which in architecture refers to design meant to be deployed and dismantled on a shorter timeframe – offers a solution. Impermanent structures often leave minimal to no lasting site impacts, cost less, and are made of recyclable or "waste" materials. Their temporary nature allows the utilization of rapid prototyping techniques to test highly experimental new technologies at minimal costs. Using Eastern philosophy and economic and social theories, this paper has made an argument for abandoning this restrictive nature of permanence in favor of adopting a transient approach to sustainability more in line with impermanence.

Keywords: Impermanence, sustainability, design

# 1. BACKGROUND

Over the past several decades, architectural design has increasingly shifted toward an expanded emphasis on sustainability. Projects like la Tour Vivante by Pierre Sartoux of Atelier SOA are awarded media attention, but even smaller, local firms have been greatly influenced by this notion of sustainability. Sustainable design has become a design paradigm which may not always directly influence, but certainly challenges almost every work of architecture in contemporary times. The implications of designing and constructing sustainably may be more apparent in commercial construction, but they are equally significant for residential design.

With such a focus on sustainably, it becomes incredibly important to examine how this term is being defined and quantified, and how new, often overlooked approaches can prove more effective in reaching the end goal. This paper focuses on the dichotomy between permanent and impermanent architecture. Permanent architecture refers to projects with a long expected lifespan that are intended to stay in one location and made of durable, long-lasting materials. Impermanent architecture is classified as such based on a shorter intended lifespan, an ability to move easily between locations, and/or a use of short-term or up-cycled building materials. This paper explains the place of impermanent architecture within the realm of sustainable design.

Sustainability, as a construct, is perhaps harder to define than the above terms. According to the World Commission on Environment and Development's world-famous Brundtland report *Our Common Future*, sustainability is defined as that which "meets the needs of current generations without compromising the ability of future generations to meet their own needs" (WCED, 1987, p. 45). This is perhaps the most widely accepted definition, but it is by no means without room for interpretation. Official goals, as in government or politics, are "purposely vague and general" (Kerr, 1995, p. 7). These goals can be seen as high acceptance, but low quality, as the authors must often embrace ambiguity to develop a definition that can be applied to every circumstance. A vague problem statement generally leads to multiple approaches, each with varying degrees of effectiveness, which is likely why John Drexhage and Deborah Murphy of the International Institute for Sustainable Development feel that, "sustainable development has not found the political entry points to make real progress" (2010).

To ground this somewhat vague definition, I have turned to other organizations that have developed more specific standpoints or standards for the design of sustainable architecture. Of these, I have discussed three of the major authorities: the USGBC, the International Living Building Institute, and William McDonough. I have analyzed each of these sources for a more concrete definition of sustainability, a means of quantifying success, an insight into how they might define sustainable buildings (in terms of impermanence vs. permanence), and a level of inclusion for impermanent design.

According to the USGBC's Minimum Program Requirements, "all LEED projects must be designed for, constructed on, and operated on a permanent location on already existing land. LEED projects shall not consist of mobile structures, equipment, or vehicles. No building or space that is designed to move at any point in its lifetime may pursue LEED Certification" (2011, p. 2). This stipulation completely disregards environmental benefits that can be achieved from impermanent or mobile projects, denying an entire realm of architectural design. The Living Building Challenge also characterizes buildings as those which are "created for permanent use," but as a model it can also be applied to renovations, landscapes or infrastructures, and neighborhoods (International Living Building Institute, 2010, p. 8). Here, impermanent architecture would likely fall under the category of landscape or infrastructures, but at least in this regard it could still be considered for its environmental benefits.

The Congress for the New Urbanism in their "Canons of Sustainable Architecture and Urbanism" has this to say on impermanence: "Human interventions in the built environment tend to be long lived and have long-term impacts; therefore, design and financing must recognize long life and permanence rather than transience" (Moule, Dittmar, & Polyzoides, 2011, p. 2). This principle argues for permanence on the basis that interventions tend to be permanent. It neglects to ask the most important question: *should* the interventions be permanent? Maintaining permanence as a tenet of sustainability only because it has been viewed that way in the past is a stagnant approach which has no place in an ever-evolving architectural field.

Lastly, architect William McDonough, author of *Cradle to Cradle*, does not have a concrete framework for assessing the sustainable qualities of a building, which perhaps is to his benefit. He speaks instead of the wasted value of products sitting in landfills, the "linear, one-way *cradle-to-grave* model" (McDonough, 2002, p. 27). For McDonough, the current design process, or "attack of the one-size-fits-all" results in boring, uninspiring buildings, the monotonous repetition of which creates a "de-evolution" (McDonough, 2002, p. 119). If the current state of architectural design is decimating all forms of life around it, then perhaps a less permanent construct which could work *with* the environment is more appropriate.

## 2. THE ROLE OF ARCHITECTURE WITHIN THE SUSTAINABLE DESIGN PARADIGM

Merging these varying standpoints, sustainable design becomes that which works to reduce impact on the land or give back to the system. Unfortunately, this definition, like the others, is somehow simultaneously vague and limiting. Architecture has always been seen primarily as permanent construction whose primary objective was to leave a lasting impression, but that thinking is no longer prudent. That kind of architecture may still have its place, but there is room for impermanent architecture as well. The need for well designed, modular, temporary residential constructs to shelter families during disaster relief efforts has perhaps underscored this new opportunity to design with a set life span. In order to make this argument, I have analyzed architecture's place within the goal of sustainability.

### 2.1 Logics of Sustainability

Despite the progression of the "green" movement, the fact that sustainability does not have any set "intrinsic meaning" is often overlooked (Warner & DeCrosse, 2009). To sustain simply means "to keep up" or "prolong," and that is just one of eight definitions given by Merriam Webster (2012). To say that the purpose of or means of achieving sustainability is permanence is to use the literal definition without regard for its applicability. Humans are born, live for a period, and ultimately die; architecture must do the same. Eternal life, for individuals or buildings, is by no means possible or sustainable, as it would lead to overpopulation and a decimation of natural resources. Authors Simon Guy and Graham Farmer suggest that "a more appropriate way to understand this strategic diversity lies in abandoning the search for a true or incontestable definition of sustainable buildings, and instead treating the concept in a 'relative rather than absolute sense'" (2001, p. 140; quoting Cook and Golton, 1994, p. 684). They separate the distinct modes of sustainable thinking in architecture into six different logics (Table 1).

**Table 1: The Competing Logics of Sustainable Architecture**

| Logic | Spatial Image | Knowledge Source | Image | Technologies | Idealized Concept of Space |
|---|---|---|---|---|---|
| **Eco-Technic** | Global, Macrophysical | Technorational, Scientific | Commercial Modern | Integrated, Energy Efficient, High-tech | Integrate environmental concerns into conventional design; compact, dense. |
| **Eco-Centric** | Fragile Microbiotic | Systemic Ecology, Metaphysical Holism | Parasitic Consumer | Autonomous, Renewable, Recycled, Intermediate | Decentralized, autonomous; limited footprints; stability/integrity of biodiversity. |
| **Eco-Aesthetic** | Alienating, Anthropocentric | Sensual Postmodern Science | Iconic New Age | Pragmatic, New, Nonlinear, Organic | Reconstructed in light of new ecological knowledge; transforms consciousness. |
| Eco-Cultural | Cultural Context, Regional | Phenomenology, Cultural Ecology | Authentic, Harmonious | Local, Low-tech, Common, Vernacular | Adapted to local and bioregional physical and cultural characteristics. |
| Eco-Medical | Polluted, Hazardous | Medical, Clinical Ecology | Healthy, Caring | Passive, Nontoxic, Natural, Tactile | Natural, tactile environment; ensures health and well-being of individuals. |
| Eco-Social | Social Context, Heirarchical | Sociology, Social Ecology | Democratic, Individual | Flexible, Participatory | Decentralized "organic," nonheirarchical, and participatory communities. |

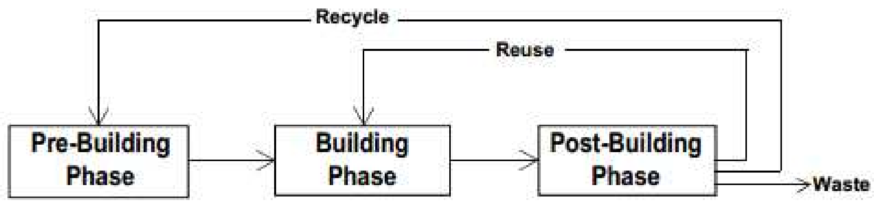
(Table 1, Guy & Farmer, p.141)

Of these six, the first three become vital to the debate between permanent and impermanent architecture. Permanent design can most appropriately be seen as a combination of the eco-technic and eco-aesthetic logics. The current approach to sustainable development is through the use of high-technology embedded in permanent buildings to maximize efficiency. The argument for this lies in the belief that it is possible to, "overcome the environmental crisis without leaving the path of modernization" (Spaargaren & Mol, 1992, p. 334). This eco-technic approach is often faulty, and where it stumbles, it couples with the eco-aesthetic logic, a sort of "fake it till you make it" method to sustainable development which looks to the architecture as "an iconic expression of societal values" which should "act to inspire and convey an increasing identification with nature" rather than actually working to solve the issue (Guy & Farmer, 2001, p. 143). This is essentially the architectural equivalent of cancer awareness car magnets.

As the logic that best applies itself to impermanent architecture, the eco-centric logic calls for a "radical approach to rethinking building design and production" (Guy & Farmer, 2001, p. 143). This logic sees the land "not as a commodity to be bought and sold, but rather as a community of which humans are an integral part" (Leopold, 1949, p. 223-224). Buildings are unnatural and disruptive consumption hogs. According to Steve Curwell and Ian Cooper, authors of "The Implications of Urban Sustainability," "each building is an act against nature" which acts as a parasite "rendering part of earth sterile" (1998, p 17-27). This current condition of architectural design is by no means sustainable.

## 2.2 Phases of Sustainability

When thinking of the different phases of a building's lifecycle, the costs and opportunities of sustainability can be considered at each step (Fig 1). Jong-Jin Kim and Brenda Rigdon divide sustainable considerations during the building process into six components: lifespan, durability, maintenance requirements, reusability, recyclability, and biodegradability. The study was limited to conventional materials but could easily be applied to impermanent construction.




(Fig. 1, Jong-Jin & Rigdon)

The reuse of durable, low maintenance materials is a relatively common component of impermanent projects, especially those which could later biodegrade or be recycled. Even in more permanent projects, these types of building materials have huge benefits. Consider the Hidden Villa in Los Altos Hills, California which uses straw bales to create walls and partitions that insulate from the elements. These bales are a locally sourced by-product of farming and would otherwise go to waste (Sassi, 2006, p. 172). Another benefit of impermanent construction is that it does not have to weigh the costs/benefits of purchasing longer-lasting materials. These materials are purchased in an effort to save money/energy in replacement costs, but often outlive the building's lifespan or are replaced before necessary simply for aesthetic purposes. Materials like these are even less appropriate for temporary residential shelters, although without an open discourse on impermanent design, these default materials are likely the only ones that will be considered.

### 2.3 A Culture of Sustainability

Awareness of and attitudes toward impermanence are greatly dependent on culture. While Western cultures tend to see impermanence as a function of "improvisation and convenience, a making-do until there is time or money" (Chaplin, 2005, p. 79), the view of impermanence by those in the East, particularly in Japanese culture, is "grounded in Buddhist doctrine" (Steineck, 2007, p.34) and has a much more positive connotation. Impermanence is a central tenet of Buddhism, known in Japanese as *mujokan,* which permeates the Japanese approach to design and construction. For those in the East, there is an embedded uncertainty in the act of construction itself, where "things are never fully designed, but are always in a state of being designed" (Chaplin, 2005, p. 79). Kisho Kurokawa, Japanese architect and founder of the Metabolist movement, argues for impermanence, saying, "The ideal that human beings must strive for is not to conquer nature… but to live as a part of nature, in accord with its rules" (Belfiore, 2011). This stands in stark contrast to permanent construction. Examples of Buddhist impermanence in practice are far-reaching and include everything from Japanese urban development to the ritualistic reconstruction of the Shinto temple at Ise, which emphases the sanctity of the earth over the built form (Chaplin, 2005, p. 80). For Buddhists, even the "permanent" is impermanent. The Japanese city, haphazard yet efficient and quick to adapt, is an excellent example of this preference, and this idea of impermanence speaks to the mindset needed to advance sustainable practice. We must learn to accept that, like us, works of architecture are not immortal, and also like us, the land we build on is not invincible. This will enable us to refocus on preservation of natural resources and reduced impact on the land rather than preservation of design.

Because everything is fleeting to the East, there is almost no emphasis on durability. In many ways this is a more sustainable practice, since a building's collective lifetime cannot surpass the smallest lifespan of any of its components (Banaag, 2001, p. 3). Under this logic, valuable resources are not being wasted in making a material more durable than necessary. Arata Isozaki mirrors this sentiment in an interview from 1999, saying, "Architecture is always growing or decaying… and if the lives of buildings move in the same direction that people's do, they will surely encounter change and eventually their end" (Isozaki, 1999, p. 112). Architect Sarah Chaplin expands on this, questioning, "Why make something to last, when it simply will not… when a more powerful means of expression can be obtained from its impermanence?" (2005, p. 81) An example of such expression can be seen in Frei Otto and Sigeru Ban's Japan Pavilion, an impermanent structure of recycled paper which would be again recycled after the expo. The design process, executed with minimal technology, included joints supported with tape (Fig 2.).


(Fig. 2, Design Boom, courtesy Princeton Architectural Press)

**2.4 Western Adaptations in Eastern Culture**

Western economist E.F. Schumacher adapted much of these Eastern philosophies to create an economic theory known as "Buddhist economics." While he is known for saying, "the central concept of wisdom is permanence," Schumacher is not speaking of material products, but rather the permanence of our environment as a whole (Fullerton, 2008). In fact, much of his economic theory stems from his study of Gandhi and his objections to man's "craze for machinery" (Weber 1999). While Schumacher's initial emphasis was on job loss through automation, his ideas can easily be applied to sustainable architecture. In this vein, founder and president of the sustainable economic collaborative Capital Institute quotes Einstein's famous warning: "'We can't solve problems by using the same kind of thinking we used when we created the problems.' Relying on technology solutions alone to solve our sustainability challenges, which are largely the product of technological advances, is not wise. We must think differently…" (Fullerton, 2008). Perhaps Schumacher is right in saying that "any intelligent fool can make things bigger, more complex…" (Schumacher 1973); we should focus our attention on making things *better,* and this will most likely require a paradigm shift in our most fundamental ideas of how to design sustainably. Because evolutionary growth will never stop or be complete, permanence is effectively an unattainable goal, yet designs continue to attempt a counterintuitive degree of permanence. Moving forward, impermanence is the mechanism by which we can secure the permanence of our existence. When asked if he felt that the ideas of Buddhist economics could work in the Western world, Schumacher poignantly replied, "The West is just as much capable of common sense as anybody else… we can't go on building buildings like this" (Fullerton 1977). We should abandon a culture of permanence in favor of a culture of growth.

## 3. AN IMPERMANENT FUTURE

Despite the pervading influence of permanence thinking, the field of architecture is on the cusp of change. The increasingly important goals of sustainability require a new design paradigm that can better foster and enable sustainable strategies. This desperately needed new paradigm has its basis in the way of impermanence. This is not to say that there is no longer a place for any permanent design, but rather that a place must be made for impermanent thinking, as it is much better able to adapt to society's changing needs, rapid technological advances, and scarce resources. Impermanent thinking challenges design to embrace and be influenced by an unalienable truth that individuals, especially those in the Western world, have a hard time accepting: nothing is permanent. Continuing on a path of strictly permanent thinking would lead to the continued wasting of resources and a lost opportunity to truly improve the state of our environment. This paper sheds light on the impermanence of permanent thinking and the importance of impermanent thinking. As such, it opens the floor for further discourse, research, and design development in the realm of impermanent design in both residential and commercial sectors.

### 4. ACKNOWLEDGEMENTS

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# MAXIMIZING DAYLIGHT USE POTENTIAL IN RETAIL SHOPPING ENVIRONMENTS IN THE CONTEXT OF DHAKA, BANGLADESH

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## ABTRACT

In the recent times with the increase in the population, the number of retail shopping environments has increased significantly in Dhaka city. But these shopping environments are developing into high consumption areas of electricity resulting from artificially light design approach. In this study, it was found that the energy consumption is rising because of the minimal or no use of daylight and natural ventilation.

A field based case study was conducted to review the daylight inclusion in the design of retail shopping environments representing the historical periods of 1950-70, 1971-80, 1981-90, 1991-2000, 2001-2011. In this research in addition to field work, parametric study was done to identify the effect of design factors/parameters relating to daylight. The main focus was to develop a causal relation between the parameters of the shopping environments to maximize the use of daylight. The parameters which were considered in this study were- width, height and depth of the shops; the depth of the corridor between two rows of shops; the height and width of the light wells. All the parametric relations were derived to the width of the shop. Daylight level were measured and compared with the given level in the Bangladesh National Building Code (BNBC) code.

It was found that shopping environments play an important role in energy consumption in urban areas and little or no utilization of daylight contribute to this energy demand. This is of particular significance in an environment where dwindling fossil sources of energy and an increasing energy demand created by positive economic growth pose a challenge for the building industry stake holders.

**Keywords:** Daylight, Parametric Study, Retail Shopping Environments

## 1. INTRODUCTION

Dhaka city has an approximate 400 year old history where trading and commerce played an important role in its growth. The retail shopping environments of Dhaka city evolved over the whole time period. Before 1950 ‘Chawk Bazar’, ‘Babu bazar’ to name but a few were the major places for retail shopping activities in Dhaka city. Between 1950- 1960, ‘New Market’ was established as a retail shopping market to serve Dhanmondi, an planned residential area (Fig. 01). In 1981- 1990 some multistoried markets started to emerge. ‘Sharif Market’ and ‘Century Arcade’ (Fig. 02) are the examples of that period.

Between 1990- 2000 more multistoried retail markets were established with the amenities like escalator and air conditioning. ‘Eastern Plaza’, ‘Karnaphuli garden city shopping complex’, ‘Russel Square’ is some of the examples of that period. After 2000 the construction of retail markets expanded, between 2001-2010 lot of markets of similar typology were established throughout the Dhaka city. ‘Plaza A R’, ‘Bosundhara City’(Fig. 03)., ‘Anam Rangs Plaza’ etc are some of the example of this time. . These shopping environments are developing as introvert high energy consuming, mechanically controlled areas leading to poor utilization of daylight and natural ventilation.

*Fig. 01: New Market (2012)*

*Fig.2: Century Arcade (2012)*

*Fig.3: Basundhara City (2012)*

The utilization of daylight will lead to a decrease of energy use during daytime in retail shopping environment. As the shopping facilities are open until 8pm the use of electricity for the lighting would be necessary for only 3-4 hours. This amount of energy necessary for this service can be provided by the use of renewable energy, partially or entirely. The utilization of natural ventilation would render the opportunity to use passive cooling mechanisms in the shopping facilities. This will also decrease the use of energy for air conditioning and air circulation. In residences or commercial office spaces it is more expensive to cool a building than to light a building. But the amount of energy used for lighting in the shopping areas is almost 50% of the total energy consumption of the facility (Debnath, K. B, 2012).

## 2. EVOLUTION OF RETAIL COMMERCIAL GROWTH IN DHAKA

Cities are products of the changing circumstances, culture, societies, politics and economy of their origin and growth. The commercial activities in a city are as old as the city. (Hossain, N. 2002) Dhaka, the capital city of a Bangladesh, is situated on the northern bank of river Buriganga. The antiquity of Dhaka as a settlement can be dated 7$^{th}$ century AD when it was part of the Buddhist kingdom of Kamrup and an image of Harissankara dated 11-12$^{th}$ century AD. (Islam, N. 1996) These relics suggest that human habitation started from approximately 1400 years ago. Dhaka was established as a town approximately 400 years ago. In different periods of history the city expanded due to significant developments in trade and commerce. This time period can be divided into six stages. They are - Pre-mughal hindu Period (Before 1608), Mughal Period (1608-1764), The rule of the East India Company (1764-1857), British Colonization (1858-1947), Pakistan Period (1947-1971) and Bangladesh Period (1971-2011). It seems that the shopping environments are evolving towards the multistoried development. But the energy consumption of these buildings are increasing due to the less or no use of daylight and natural ventilation and increase in the use of artificial ventilation and lighting. (Debnath, K. B, 2012).

## 3. METHODOLOGY

In this study, from literature review and the field study the evolution of the retail shopping environments of Dhaka city was analyzed. From this evolution study the problems of the retail developments regarding the day light utilization and natural ventilation was investigated. In the later stage parametric studies were conducted to find out the parametric solutions for maximizing the utilization of day light in shopping environments.

## 4. MICROCLIMATE OF DHAKA CITY

Dhaka experiences a hot, wet and humid tropical climate. The city has a distinct monsoonal season, with an annual average temperature of 27.5 °C (81.5 °F) and monthly means varying between 19.5 °C (67 °F) in January and 32 °C (90 °F) in April. Approximately 87% of the annual average rainfall of 2,121 millimeters (83.5 in) occurs between May and October. Increasing air and water pollution emanating from traffic congestion and industrial waste are serious problems affecting public health and the quality of life in the city (Mondal, M. Abdul Latif, 2006). Water bodies and wetlands around Dhaka are facing destruction as these are being filled up to construct multi-storied buildings and other real estate developments. ‘Coupled with pollution, such erosion of natural habitats threatens to destroy much of the regional biodiversity’ (Mondal, M. Abdul Latif, 2006).

Throughout the year the availability of daylight is a major environmental asset for Dhaka. Solar direct and diffuse radiations during these months are the major sources of daylight in buildings. In case of shopping environments BNBC made standards of light level is minimum 300 lux in the shop at work top level and minimum 500 lux in display area. Since solar radiation is a major source of light in the energy saving approach in spite of its heat and glare, the maximum use of daylight and natural ventilation is a major consideration to achieve environmentally responsiveness in shopping environment.

# 5. METHODS AND TOOL FOR PERFORMATIVE EVALUATION

Daylight analysis means using a manual calculation or computer program to model, mathematically the interplay of lighting level within a building. There are wide range of mathematical models used for this purpose, all of which vary significantly in both case of implementation and comprehensiveness. ECOTECT is such type of environmental design tool, which couples an intuitive 3D modeling interface with extensive solar, thermal, lighting, acoustics and cost analysis functions. Nicky Taylor validated ECOTECT as part of his research work for the degree of Bachelor of Engineering (Hors.) form Department of Environmental Engineering at University of Western Australia in 2002. He showed in his research that the mean errors of the estimated results are less than 2%, indicating a reasonable degree of accuracy (Hossain.S. 2007).

For the software the input data were- In 3D model for the ray tracing precision 4096 spherical rays per sample point, design sky illuminance was 11000 lux.sky luminance distribution model was CIE overcast sky condition, the window cleanliness was average (x 0.90), the orientation were North, South, East, West, Weather file for Dhaka city (prepared by the U.S. Department of Energy) and the context was urban, fully natural ventilated building, operating time 12:30PM at 1$^{st}$ April.

In the modeling the ceiling material was 10mm suspended white plaster board ceiling, plus 50mm insulation, with remainder (150mm) joists as air gap. The partition walls were of 80mm framed wall as air gap, with 10mm white plaster board either side. In the model the apertures are containing single glazed glass with aluminum frame, All the shops are in a row layout, The floors are 100mm thick suspended concrete floor plus ceramic tiles and plaster ceiling underneath., Only three type of floor to floor height is considered- 8', 10', 12', The shops are maintaining the U shaped display counter, In the corridors the material of railing is Stainless steel with circular section.

# 6. COMPARISON OF ENVIRONMENTAL RESPONSIVENESS

### 6.1 Utilization of daylight

In Shakhari bazaar during the pre-mughal hindu period (Before 1608) people mainly depended on the daylight. The Chawk bazaar was depended on daylights from Mughal Period (1608-1764) to British Colonization (1858-1947). But after the establishment of New Market in Pakistan period artificial lighting was introduced in retail shopping areas. But the design of the New Market enabled it to use the daylight. In Bangladesh time period, the Polton Super Market was also following the footsteps of the New Market. A simulation study was conducted on existing built spaces to evaluate percentage of daylight received in terms of area (Fig. 04). It was found that in the case of Polton Super Market the circulation corridor was not spacious as in the case of New Market hence the amount of area receiving daylight is less. Centaury Arcade has also utilized daylight. But they had to depend on artificial lighting due to the greater depth of the building. The Eastern plaza was a completely artificially light shopping environment. (Fig. 04) There are some apertures in the building but they are not sufficient. Basundhara city uses little daylight due to planning approach where shops on the front side create s a barrier. The atrium mostly lights the circulation around it. But most of the shops are depended on artificial lighting even in day time. So the daylight use is higher than Eastern plaza but not significant (Showed in Fig. 04).

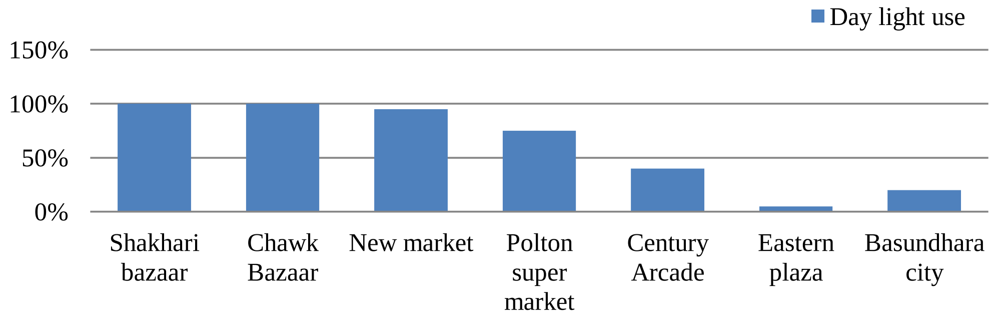



*Fig. 04: Simulated Day light Use in Retail Shopping Environments expressed in Percentage of Floor Area*

### 6.2 Energy Consumption

From pre-mughal hindu period (Before 1608) to British Colonization (1858-1947) all the shopping environments were not using any electricity.

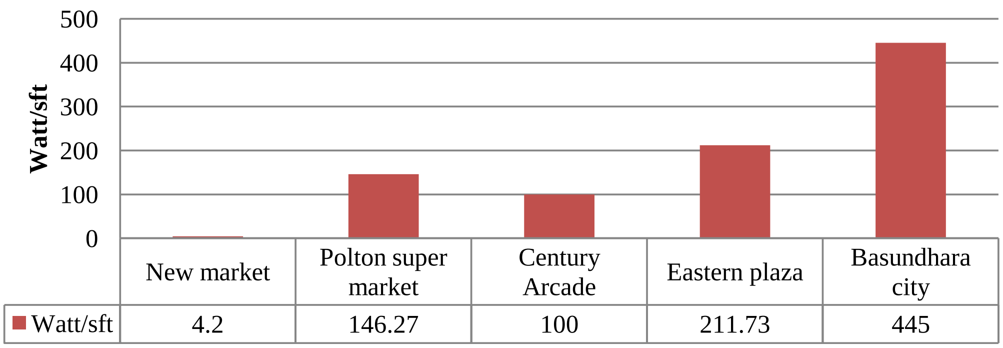



*Fig. 05:Electricity Use per square feet in Retail Shopping Environments Expressed in Watt per sft Floor Area*

From New Market to Basundhara City, the energy consumption is rising (Showed in Fig. 05). The use of electricity in per square feet is rising with the increase in the use of artificial lighting and the reduced daylight. The energy consumption was measured from the monthly electric bills. This data is showing the maximum energy consumption as it was measured in the month of April after the Eid festival. Because of the festival the number of occupants reaches to the top causing high energy consumption. It was found that these types of mechanically controlled multistoried shopping environments are increasing the use of energy in a high rate. These are not environmentally responsive design solutions.

# 7. PARAMETRIC STUDY

## 7.1 Introduction

During the study two distinctive type of shop layouts were found. One type of shop has one side which comes with the contact with the outer surface. This can be used as an aperture for daylight. The circulation corridor is on the opposite side of the aperture surface (Showed in Fig. 06). Other than this aperture all other surface is surface is closed. The second type of shop has the circulation corridor in on one side and this corridor is the source of daylight (Showed in Fig. 07).

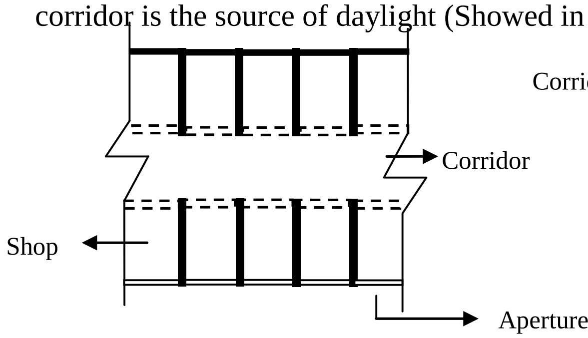



*Fig. 06: Shops with apertures in one side*

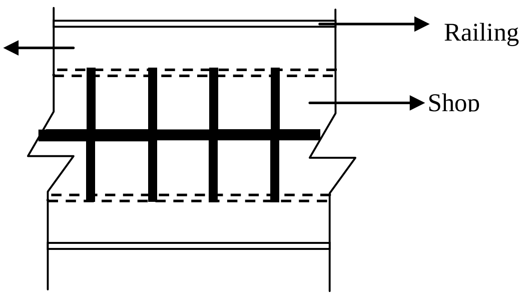



*Fig. 07: Shops with corridor in one side*

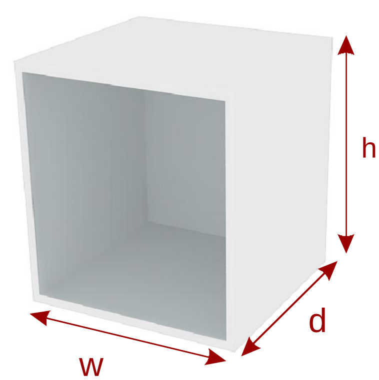
For this reason, the total study is divided into 4 stages. Firstly the single shop, where two types of organization can be found. One is the shop facing inward with an exposed surface towards the exterior and other is the shop facing outward with a corridor in front. Second is the organization of the multiple shops. Here the relation between the lengths of the multiple shop organization can be analyzed. Thirdly the relation of the parameters in case of horizontal expansion is going to be simulated. And fourthly in case of the vertical expansion the parametric relation is going to be analyzed. In the tables- Green is the acceptable value (If the light level at last end of shop is greater than 300 lux ) and blue is unacceptable value (If the light level at last end of shop is less than 300 lux ).

## 7.2 Shops with Single Side Aperture

### 7.2.1 Relation between Height, Width, Depth for a single shop with aperture on external side

| | h=8’ | | | h=10’ | | | h=12’ | | |
|---|---|---|---|---|---|---|---|---|---|
| w:d | 1:1 | 1:2 | 1:3 | 1:1 | 1:2 | 1:3 | 1:1 | 1:2 | 1:3 |
| 100% | | | | | | | | | |
| 50% | | | | | | | | | |
| 25% | | | | | | | | | |

*Fig. 08: Relation between Height (h), Width (w) and Depth (d) for a single shop with aperture on external side*



For h=8', 10', 12' and 50-100% opening, **d= [1-2] w**

For h=8', 10', 12' and 25% opening, **d= w**

If the floor to floor height is 8', 10' or 12' and the shops has a exterior surface with a 50-100% aperture with clear glass the depth of the shop should be equal or maximum double to the width of the shop (Fig. 08). In case of exterior surface with a 25% aperture with clear glass the depth of the shop should be equal to the width of the shop. The greater amount of depth than the above mentioned proportion will create less than 300 lux of light.

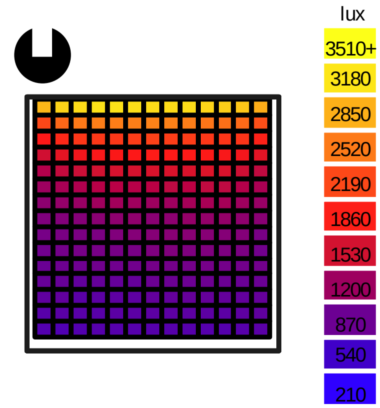
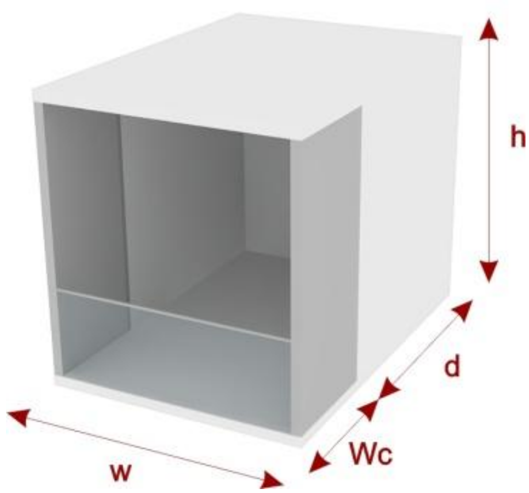



*Fig. 09: Daylight level at work top (h=8', w:d=1:1 and Aperture 100%)*

**7.2.2 Relation between Height, Width, Depth for a single shop with peripheral corridor on one side**



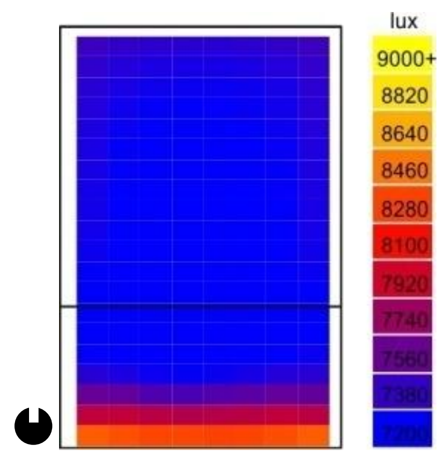




*Fig. 10: Daylight level at work top (h=8', w:d=1:1 and Wc= 0.5w)*

For h=8'
**d= [1-2] w**
**Wc= [.5-1] w**

For h=10', 12'
**d= [1-2] w**
**Wc= [.5-1.5] w**

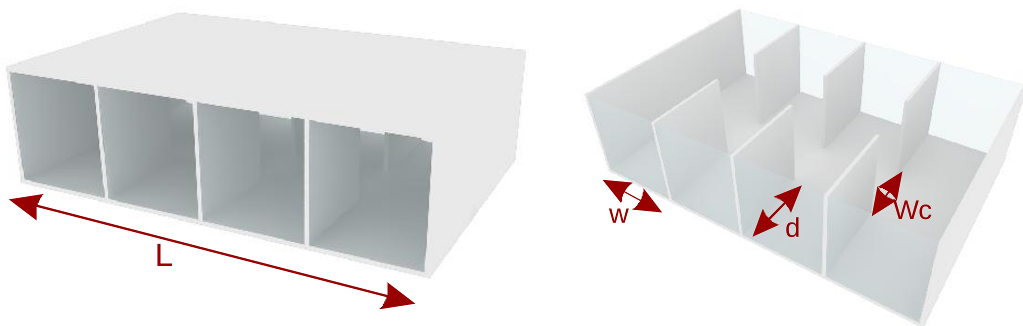
| | h=8' | | | h=10' | | | h=12' | | |
|---|---|---|---|---|---|---|---|---|---|
| w:d / Wc | 1:1 | 1:2 | 1:3 | 1:1 | 1:2 | 1:3 | 1:1 | 1:2 | 1:3 |
| 0.5w | | | | | | | | | |
| w | | | | | | | | | |
| 1.5w | | | | | | | | | |
| 2w | | | | | | | | | |
| 2.5w | | | | | | | | | |

*Fig. 11: Relation between Height (h), Width (w) and Depth (d) for a single shop with peripheral corridor on one side*

If the floor to floor height is 8', 10'or 12' and a corridor in front of the shop, then the depth of the shop should be equal or maximum double to the width of the shop (Fig. 11). In this case the width of the corridor should be 0.5 to equal (for 8') or 1.5 times (for 10' and 12') than that of the width of the shop.

## 7.3 Multiple shops

### 7.3.1 Relation between Height, Width, Depth and Width of the corridor with aperture on one side of the shop for daylight



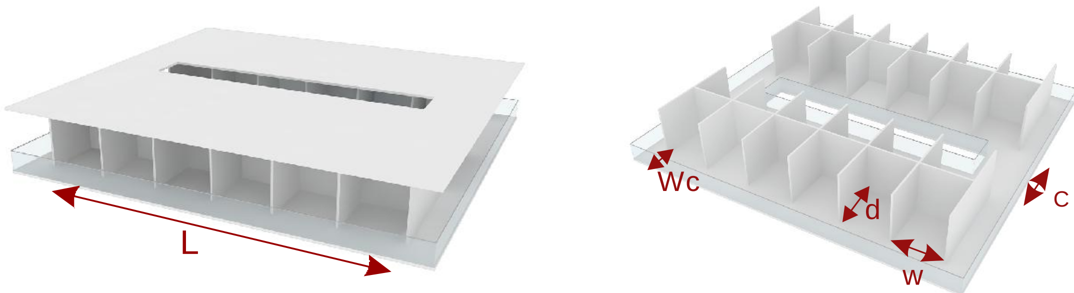

| Height | | h=8' | | | h=10' | | | h=12' | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Aperture | w:d / Wc | 1:1 | 1:2 | 1:3 | 1:1 | 1:2 | 1:3 | 1:1 | 1:2 | 1:3 |
| 100% | 0.5w | | | | | | | | | |
| | w | | | | | | | | | |
| | 1.5w | | | | | | | | | |
| | 2w | | | | | | | | | |
| | 2.5w | | | | | | | | | |
| 50% | 0.5w | | | | | | | | | |
| | w | | | | | | | | | |
| | 1.5w | | | | | | | | | |
| | 2w | | | | | | | | | |
| | 2.5w | | | | | | | | | |

*Fig. 12: Relation between Height (h), Width (w), Depth (d) and Width of the corridor (Wc) with aperture on one side of the shop for daylight*

For h=8', 10', 12' and 100% opening, **d= [1-2] w, Wc= [0.5-1.5] w**
For h=8', 10', 12' and 50% opening, **d= [1-2] w, Wc= [0.5-1] w**
For h=8', 10', 12' multiple shops with 25% opening not acceptable
In case of the floor to floor height is 8', 10' or 12' and the shops has a exterior surface with a 50-100% aperture with clear glass, the depth of the shop should be equal or maximum double to the width of the shop. Exterior surface with a 25% or less aperture is not acceptable. If the shops have an exterior surface with a 100% aperture with clear glass the width of the corridor should be 0.5 to 1.5 times of the width of the shop. In case of 50% aperture the width of the corridor should be 0.5 to 1 times of the width of the shop. (Fig. 12)

## 7.4 Multiple shops with horizontal layers

### 7.4.1 Relation between Floor height, Width of the corridor and width of the light well for shops with aperture on one side




| Height | h=8' | | | | | h=10' | | | | | h=12' | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wc / C | .5w | w | 1.5 w | 2w | 2.5 w | .5w | w | 1.5w | 2w | 2.5 w | .5 w | w | 1.5w | 2 w | 2.5 w |
| 0.25w | | | | | | | | | | | | | | | |
| 0.5w | | | | | | | | | | | | | | | |
| w | | | | | | | | | | | | | | | |
| 1.5w | | | | | | | | | | | | | | | |
| 2w | | | | | | | | | | | | | | | |
| 2.5w | | | | | | | | | | | | | | | |
| 3w | | | | | | | | | | | | | | | |

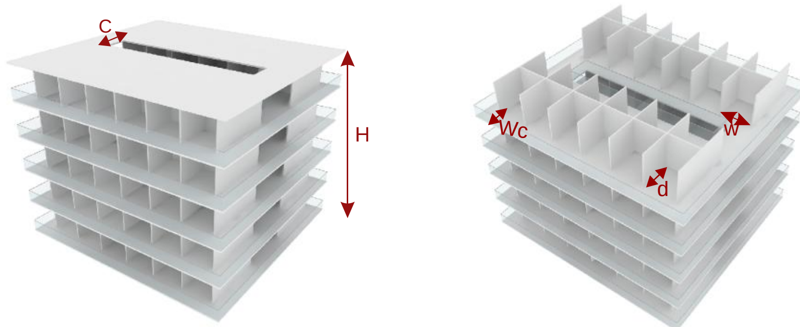
*Fig. 13: Relation between Floor height (h), Width of the corridor (Wc) and width of the light well (c) for shops with aperture on one side*

For h= 8' **C= [1-2] w** when **Wc = [0.5-1] w**
For h= 12' **C= [1-2] w** when **Wc = [0.5-2] w**
For h= 10' **C= [1-2] w** when **Wc = [0.5-2] w**

When the shops develop multiple layers horizontally, a light well is needed for the utilization of daylight and natural ventilation features. The width of the light well should be equal or maximum double to the width of the shop when the floor to floor height is 8', 10'or 12'. But when the floor to floor height is 8', the width of corridor should be 0.5 to 1 times of the width of the shop. If the floor to floor height is 10'or 12', the width of corridor should be 0.5 to 2 times of the width of the shop. (Fig. 13)

## 7.5 Multiple shops with Vertical layers

### 7.5.1 Relation between Building height, Floor to floor height, width of the corridor and width of the light well for shop with corridor on one side



| Height | h=8' | | | | | h=10' | | | | | h=12' | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| h / C | 2h | 3h | 4h | 5h | 6h | 2h | 3h | 4h | 5h | 6h | 2h | 3h | 4h | 5h | 6h |
| w | | | | | | | | | | | | | | | |
| 2w | | | | | | | | | | | | | | | |
| 3w | | | | | | | | | | | | | | | |
| 4w | | | | | | | | | | | | | | | |
| 5w | | | | | | | | | | | | | | | |
| 6w | | | | | | | | | | | | | | | |

*Fig. 14: Relation between Building height (H), Floor to floor height (h), width of the corridor (Wc) and width of the light well (C) for shop with corridor on one side*

For h= 8', 10', 12'  **c=nw** when **H=nh**  Here, n>1 and when Wc= 0.5w

When the shops develop multiple layers horizontally and vertically, the width of the light well should be 'n' times of the width of the shop in all cases of the floor to floor height is 8', 10' or 12' (Fig. 14). The height of the light well should be 'n' times of the floor to floor height. The number of floor should be more than 1.

## 8. CONCLUSION

The issue presented in this paper can be regarded as the beginning of this complex but important relation between building morphology and daylight in the local context. The findings illustrates that it is greater clarity in design is required retail shopping areas in a Hot-humid climate like Bangladesh. From these parametric relations the architects can find possible indications in designing a retail shopping environment optimizing daylight availability. Although there is other factors like urban density or impact of adjacent buildings can affect the daylight availability. The scope of this research allowed the study in an simplified situation omitting the effect of adjacent buildings. But detail study and research can be undertaken to observe the above effects. This study provides an initial but important step for finding out the basic parametric relation between the building morphology and its environmental responsiveness.

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# HIGH PERFORMANCE FACADES: THE EFFECT OF SUN BREAKERS ON DAYLIGHTING PERFORMANCE AND ENERGY CONSUMPTION IN SOUTH ORIENTED OFFICE SPACES

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**ABSTRACT:**

Daylighting is considered one of the main passive strategies for enhancing indoor spaces quality. Shading device is usually used to prevent excessive sunlight from delivering into the building, especially in clear-sunny sky environment. The use of a per-formative shading device can help in reducing both cooling and lighting loads, as well as improving the quality of the space. Nevertheless if such devices are not designed with care it may cause to admitting more sun rays than needed or result into poor daylit spaces. Sun breakers are believed to enhance the performance of southern faced spaces, as it provides protection from the excessive solar rays which have direct effect on the cooling loads.
This paper investigates the effect of using sun breakers on both daylighting and energy performance. Year-round daylighting and energy simulations were conducted for a south oriented office space, located in the city of Cairo, Egypt. Diva-for-Rhino a plug-in used to interface Radiance and Daysim was used for calculating the annual Daylight Availability of the space. While Viper another plug-in for rhino and used to interface Energy-Plus was used for annual energy consumption simulations. Sun breakers with different settings and parameters were compared and the results were analyzed for achieving the needed balance.
Results showed that the performance of sun breakers is tremendously related to its position, depth and rotation angle. The daylighting performance could be significantly enhanced; the ‘Daylit’ area percentage can reach more than 72% of the space, while the savings in the annual energy consumed had also reached up to 34%. The results also showed that there is a satisfactory balance between the daylighting solutions and the thermal ones.

*Keywords: Clear Sky, Daylighting Performance, Energy Consumption, Office Buildings, Sun Breaker*

## INTRODUCTION

Energy-conscious and environmentally responsible designs are key issues in the building industry nowadays. Simultaneously, utilization of daylight as a substitute to artificial lighting is one of the effective methods of energy saving in buildings. Good daylight design improves the quality of life and work environment by creating productive and appropriately lit spaces. Office buildings are being constructed with increasing amounts of glass in their design facades and this makes them more aesthetically pleasing. However, the downside to this trend is that such buildings, especially in hot arid countries, had great potential for year round high solar radiation. In addition, the excessive penetration of natural light into spaces could lead, in turn, to non-uniform daylight distribution and the possibility of glare phenomena occurrence. Shading devices are among the tools that could achieve visual and thermal comfort while achieving energy-saving requirements. "Sun breaker" is one of solar control and shading systems. It is a projection from the side of a building for intercepting part of the sunlight falling upon the adjacent surface taking into account sun angles that vary depending on latitude and building orientation.

Many studies were conducted to address "Sun breaker" different aspects. A study by (Dubois M. C., 1997) showed that the reduction of energy consumption was between 23-89% depending on the type of shading device used, building orientation, climate, etc.
El Zafarany A, et. al. (2011) used the monthly sun paths to define different sun breakers. The study was performed to different geographic locations in search of the cut-off date and time that best performs annually in terms of the energy consumption (Heating, cooling and lighting). Methods for generating optimal shading devices to save energy use in buildings have been proposed by (Katfan 2001) and (Marsh 2003). Their method defined the relative importance of parts of a shading device through theoretically dividing it into cells on which accumulated information of predicted hourly heating and cooling loads were laid down. A similar approach was also developed by J. Sargent et. al. (2011) and presented a new form-generating method for shading systems called SHADERADE. In another study by (M. Dubois 2000) the angle-dependent properties based on intensity of solar radiation at different solar inclination angles was investigated, on that basis, angles of more relative importance to be blocked by a shading device were defined. Defining optimum design of a shading device that leads to minimum annual energy consumption was investigated by (Manzan and Pinto 2009) using genetic algorithms. The process, however, linked shading design directly to energy consumption without specifying the optimum cut-off date.

Balancing between natural light provision and reduction of energy consumption through appropriate solar control systems was addressed in a number of studies. In a paper by M. David et. al. (2011) simple indices were proposed to compare thermal and visual efficacy of different types of solar shadings in office buildings. These indices can be derived from the results of numerical simulations that include thermal and daylighting analysis such as the Energy Plus software. Another paper by H. Shen and A. Tzempelikos (2012) presented a comprehensive analysis to study the balance between daylighting benefits and energy requirements (control of solar gains) in perimeter private office spaces with interior roller shades. It took into account glazing properties, shading properties and control together with window size, climate and orientation in an integrated daylighting and thermal manner. It became apparent that balance between visual and thermal comfort of shaded spaces especially in hot-arid clear-sky environment were hardly addressed by most of the related previous studies.

This paper investigated the impact of changing two parameters of sun breakers on daylighting and energy performance: Inclination angle and number of slats. The study was conducted for different cases of shading angles. The aim was to define the appropriate design of sun breakers that could achieve adequate daylighting performance and at the same time minimum energy consumption.

# METHODOLOGY

A typical South facing side-lit office room space was selected for investigation (Figure 1 & Table 1). The office is located in the city of Cairo, Egypt (30° N- 31° E) that enjoys a clear-sky condition most of the year.

Table 1: Dimensions and properties of the tested office space

| | | |
|---|---|---|
| **Space Parameters** | | |
| | ***Floor level*** | Zero level |
| | ***Space dimensions (m)*** | 4.00 * 7.50 * 3.00 |
| ***Walls*** | ***Reflectance*** | 50% |
| | ***Material*** | Medium Colored walls |
| | ***Wall with window*** | Double Brick Wall *(10 cm)* with EPS Insulation *(10cm)* |
| | ***U-value*** | 0.319 (W/m2-K) |
| | ***Non-tested walls*** | Adiabatic |
| ***Ceiling*** | ***Reflectance*** | 80% |
| | ***Material*** | White Colored Ceiling |
| | ***Thermal properties*** | Adiabatic |
| ***Floor*** | ***Reflectance*** | 20% |
| | ***Material*** | Wooden Floor |
| | ***Thermal properties*** | Adiabatic |
| **Window Parameters** | | |
| | ***Width (m)*** | 3.60 |
| | ***Sill (m)*** | 0.90 |
| | ***Lintel (m)*** | 2.70 |
| | ***Thermal Properties*** | Single Clear Glass 6mm |
| | ***U-value*** | 6.121 (W/m2-K) |
| **Sun Breaker Parameters** | | |
| | ***Reflectance*** | 50% |
| | ***Material*** | Medium Colored |

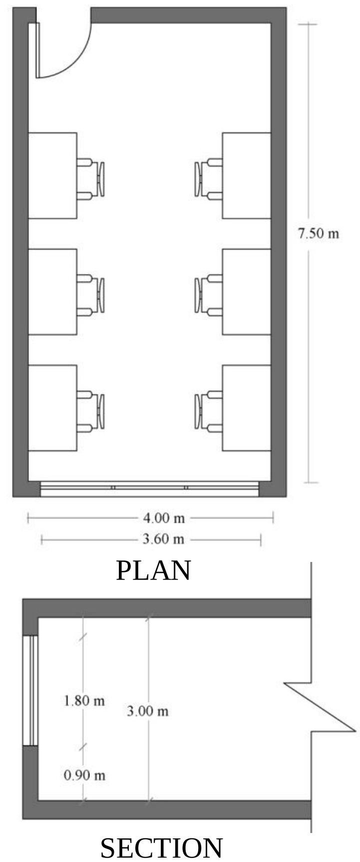
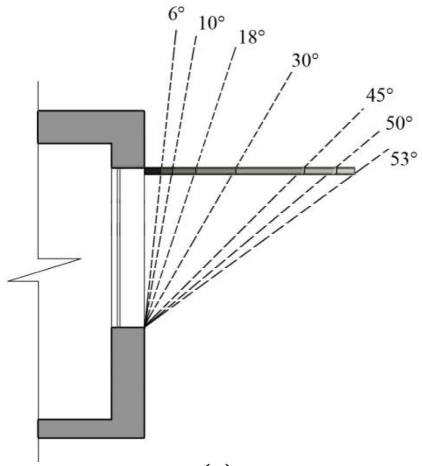
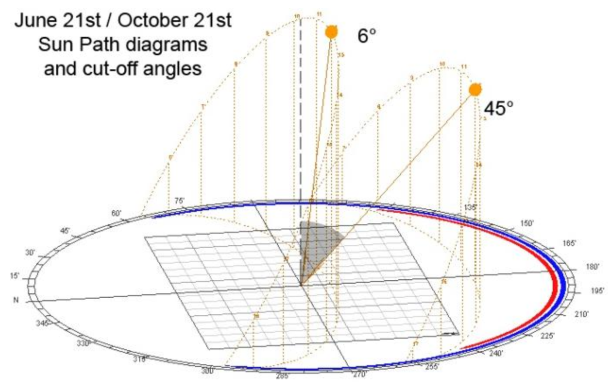


Figure 1: Architectural parameters of the tested office space

With the daily rotation of the earth around its axis, the sun appears moving in path. This trail has an inclination creating the sun zenith angles and can be used as a cutting surface that forms the extended length of the sun breaker. If the sun is higher than the used path, this will result in full shading of the fixed point in that day, if it was lower; the point will be exposed to solar radiation. As an example February\October (45° cut –off angle) breaker had to shade the sun starting from "June" until "February/ October", and would let the sun rays of the lower angles penetrate the room (the January/ November and December). Twelve solar paths were considered, each corresponds to the 21$^{st}$ day of each month of the year. However, as the annual solar path is symmetrical around the summer and winter solstices (solar paths of February and October are identical for example), only seven angles were chosen to represent the twelve months as follows: 6° (June), 10° (May/July), 18° (April/August) , 30° (March/September), 45° (February/October) , 50° (January/November) and 53° (December) (Figure 2).




(a)




(b)

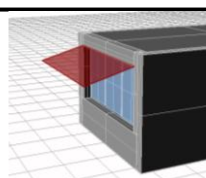
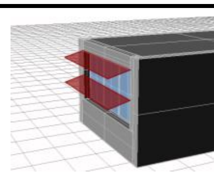
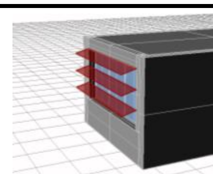
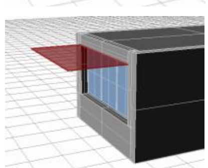
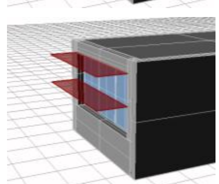
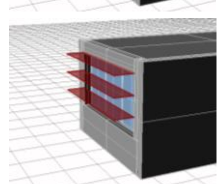
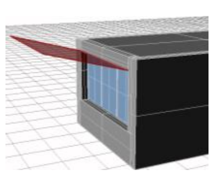
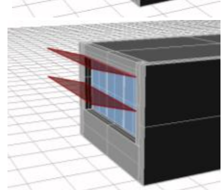
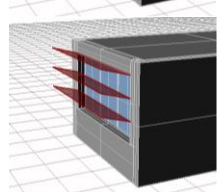
Figure 2a: Cut-off angles and its effect on sun breaker depth.
Figure 2b: Sun paths for June 21st / October 21st and the resulting cut-off angles in Cairo 30° N

For each of the cut-off dates, nine cases were modeled for the two studied parameters of sun breakers as following:

- Inclination angles: A=15° downwards, B=0°, and C= 15° upwards
- Number of slats: one, two and three

That resulted in 63 cases that were simulated for daylighting performance and energy consumption in two consecutive phases; the methodology for each phase is described in the next section. (Table 2)

Table 2: An example for the different studied cases for February\October cut-off

| Studied cases for February\October cut-off angle (45°) | | | | |
|---|---|---|---|---|
| | | Number of slats | | |
| | | **1** | **2** | **3** |
| 15° downwards | **A** |  |  |  |
| 0° | **B** |  |  |  |
| 15° upwards | **C** |  |  |  |

**Phase One: Daylight Autonomy Analysis:**

The aim of this phase was to investigate daylighting performance of the different cases. Experimentation was conducted for year round performance using Dynamic Daylight Performance Metrics (DDPM). Diva-for-Rhino (V. 2.0.0.9), a plug-in for Rhinoceros modeling software was used to interface Radiance and Daysim for annual simulation and illuminance computation. Radiance simulation parameters are shown in table (3). The time schedule used represents the annual occupied daylit hours of a typical office room (Week days from 9:00 AM to 5:00 PM). The reference plane on which daylighting performance was simulated contained 98 measuring points in a grid of 0.3m * 0.3m, at a working plane height of 0.8 m. The "Daylight Autonomy" (DA) index was addressed in this phase. It is defined as: "the percentage of the occupied hours of the year when a minimum illuminance threshold is met by daylight alone" (Reinhart and Walkenhorst, 2001). The recommended minimum illuminance value used in the tested office space is 500 Lx (IESNA 2000). The space was divided into "daylit" and "partially daylit" areas, it was assumed that areas that achieved the required threshold for at least half of the occupied time would be considered adequate (daylit). Since this is an on-going development, recommendations for DDPM criteria to evaluate daylighting performance was not presented at the time of conducting this research. However, few recommendations exist, (Reinhart C.F., 2005) suggested that the daylit area extends across the two thirds of the room adjacent to the window which corresponds to about 1.5 times the window head height. Analysis criteria for "Daylight Autonomy" adopted in this paper assumed that "daylit" areas that reached more than or equal to 60% of the space area were considered "acceptable".

Table 3: Radiance simulation parameters.

| Ambient bounces | Ambient divisions | Ambient sampling | Ambient accuracy | Ambient resolution | Direct threshold |
|---|---|---|---|---|---|
| 7 | 1000 | 20 | 0.1 | 300 | 0 |

**Phase Two: Energy Consumption Analysis**

The aim of this phase was to calculate energy consumption resulting from the use of the tested cases in terms of cooling, heating and lighting. The Viper plug-in for Rhinoceros was used to interface Energy Plus (V7.0) software for energy simulation. In order to focus on the effect of changing sun breaker parameters, all surfaces of the tested office space were assumed adiabatic, except the wall of the tested window (as illustrated in table 1). In order to neutralize the effect of the mechanical system, the Ideal Loads Air System (Purchased Air) was used. For maintaining adequate lighting, the lighting control operation was based on a dimming photo sensor that compensates the recommended minimum illuminance (500lx). The generated lighting schedules of phase one were used in this phase where the lighting load was assumed to be 11.75 W/m$^2$. Phase one occupancy schedule of the tested office space was applied in this phase at a rate of 0.1 Person/m$^2$. Heating and cooling set points were assumed to be 18°C, and 24 °C respectively. The sum of the consumed cooling, heating and lighting energy was considered the total annual energy consumption. These values were compared to the results of the space with no sun breaker. Analysis criteria adopted in this paper assumed that reaching more than 20% annual energy savings was appropriate.

## PHASE ONE RESULTS: DAYLIGHT AUTONOMY ANALYSIS

The increase in sun breaker cut-off angles was found to be inversely proportional to the percentage of daylit areas, and affected it significantly. The highest "daylit" area percentages were achieved in the case of sun-breakers with 6° cut-off angle (average 71%) and the lowest ones were at the 53° cut-off angle (average 56%). All cases with 15° upwards tilting angle were the most effective (C1, C2, and C3); the "daylit" areas had an average of 68% in all experienced cut-off angles. In the cases of horizontally extended (0° inclination angle) sun-breakers (B1, B2, and B3), "daylit" areas were found acceptable in all cases except in January\November, February\October and December cut-off angles (45°, 50°, and 53° respectively). However, daylighting performance was found the least effective, when the sun-breakers were tilted 15° downwards. The "daylit" areas were satisfactory only in six months of the year when the sun zenith angles were between 6° and 30°. As for the number of slats, there was no significant effect on daylighting measures; the differences ranged between 1% to 4% in the same cut-off angle. (Table 4)

Table 4: Daylit area percentages for the tested cases. Lighter shades indicates the adequate cases, darker shades indicates the inadequate ones.

| Cut-off Date | Cut-off angle | Daylit Area percentages in the tested cases | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | A1 | A2 | A3 | B1 | B2 | B3 | C1 | C2 | C3 |
| **June** | 6° | 71% | 71% | 70% | 71% | 71% | 71% | 72% | 71% | 72% |
| **May\July** | 10° | 68% | 70% | 69% | 71% | 70% | 71% | 71% | 71% | 72% |
| **April\August** | 18° | 64% | 66% | 65% | 65% | 70% | 69% | 70% | 71% | 71% |
| **March\September** | 30° | 57% | 59% | 61% | 64% | 65% | 65% | 68% | 70% | 70% |
| **February\October** | 45° | 54% | 52% | 55% | 57% | 60% | 59% | 65% | 66% | 64% |
| **January\November** | 50° | 51% | 51% | 51% | 56% | 59% | 58% | 64% | 64% | 64% |
| **December** | 53° | 50% | 51% | 50% | 56% | 57% | 56% | 62% | 64% | 61% |

## PHASE TWO RESULTS: ENERGY CONSUMPTION ANALYSIS

Energy savings amount was directly proportional to the cut-off angle; it increased gradually from an average of 2.7% (6° cut-off angle) and reached 27.4% when using the 50° cut-off angle. However, the average savings decreased slightly (26.9%) when using the December cut-off angle because of the increase of lighting loads. Nevertheless, sun breakers showed the same behavior achieved in daylighting performance when the slats were tilted. The horizontal and the upward tilted sun breakers increased energy savings to achieve up to 33% (case B3, 50°) and 34% (case C3, 50°). While the downward tilted one attained a maximum of and 28% (case A3, 45°) respectively. The number of slats also affected the performance but with smaller amount. The cases with single slat achieved the least savings with an average of 13.7% (case A1), 17.1% (case B1) and 14.3% (case C1). As for the cases having two slats savings reached an average of 16% (case A2), 18.4% (case B2) and 18.7% (case C2). The triple slates showed 15.5% (case A3), 18.7% (case B3) and 18.9% (case C3). As a general result all cases with the cut-off dates of February/October, January/November and December (45°, 50° and 53°) achieved more than 20% annual savings and were found acceptable. (Table 5)

Table 5: Energy savings for the tested cases. Cases with lighter shades had a higher potential for energy saving.

| Cut-off Date | Cut-off angle | Potential for energy savings in the tested cases | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | A1 | A2 | A3 | B1 | B2 | B3 | C1 | C2 | C3 |
| June | 6° | 3% | 3% | 3% | 2% | 3% | 3% | 2% | 3% | 3% |
| May\July | 10° | 4% | 5% | 4% | 4% | 6% | 5% | 4% | 6% | 5% |
| April\August | 18° | 9% | 10% | 10% | 9% | 11% | 10% | 8% | 10% | 12% |
| March\September | 30° | 16% | 19% | 17% | 15% | 18% | 18% | 14% | 19% | 19% |
| February\October | 45° | 21% | 27% | 28% | 24% | 29% | 31% | 22% | 29% | 30% |
| January\November | 50° | 21% | 24% | 24% | 24% | 31% | 33% | 24% | 32% | 34% |
| December | 53° | 22% | 24% | 23% | 24% | 31% | 31% | 26% | 32% | 29% |

## DISCUSSION AND CONCLUSION

This paper studied the effect of sun breakers cut-off angles, inclination angles, and slats number on daylighting performance and energy consumption in a South-facing office facade. Numerous simulations were conducted and the results were analyzed to evaluate the most effective parameter in each of both aspects. Although, harvesting daylighting, in hot arid climates, often causes higher energy consumption, results of the previous two sections, showed the possibility of achieving balance between them. Tilting sun breakers upwards helped in enhancing daylighting and saving energy as well. However, some other factors achieved acceptable daylighting performance but affected energy savings negatively and vise-versa. The cut-off dates of June, May\August, and April\July achieved the highest "daylit" area percentages (Average 70%) but they had the least energy savings (Average 6%). The opposite was found for the cut-off dates of February\October, January\November and December were the highest values of energy savings were attained (Average 27%)but they had the lowest "daylit" area percentages(Average 58%). In the same cut-off angle, changing the number of slats had no significant effect on daylighting measures. However, slats number influenced energy savings except in the cut-off angles of June, May/ July, and April/ August.

As a general result, nine different cases achieved the required balance between the two aspects. These were as following: (Figure 3)

- Single slat with 15° upwards inclination angle (C1) in January\November and December cut-off angles.
- Two and three slats with 15° upwards inclination angle (C2 and C3) in February\October, January\November and December cut-off angles.
- Two horizontally extended slats (B2: 0° inclination angle) in February\October cut-off angle.

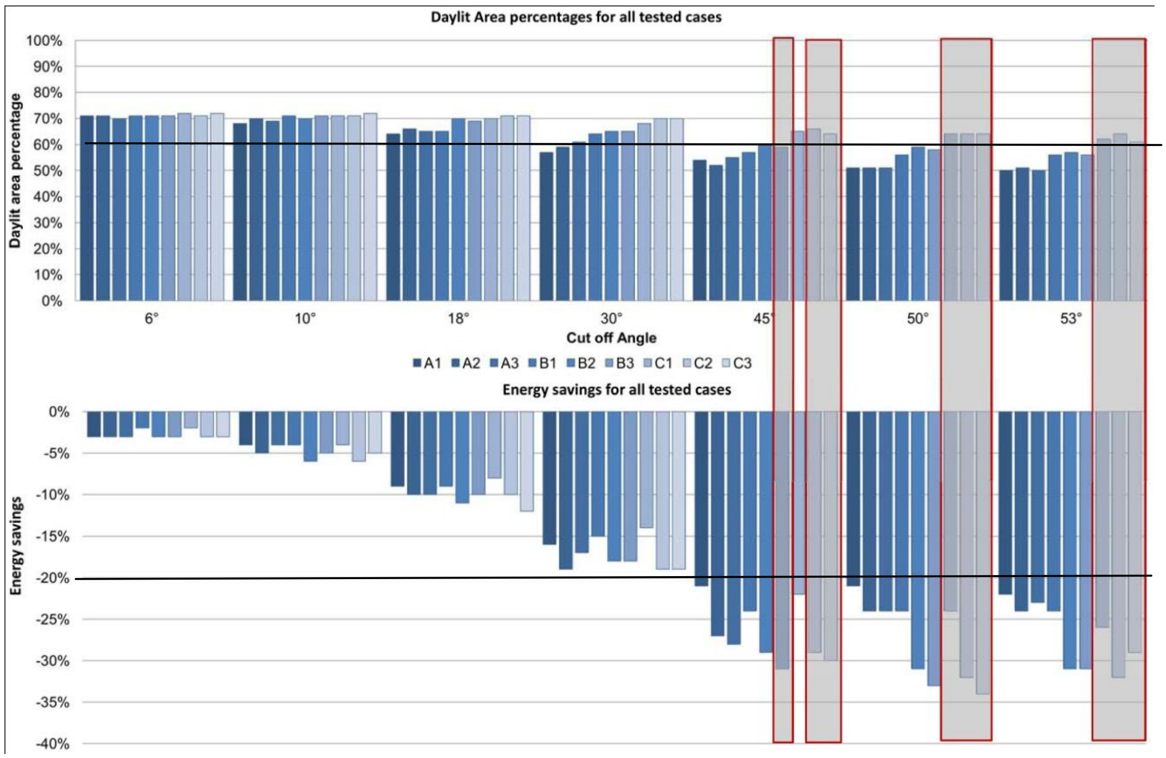



Figure 3: 'Daylit' area percentages and energy savings for all tested cases. The nine cases where balance between daylighting performance and energy savings was achieved are highlighted.

A satisfactory balance between achieving efficient energy savings and daylighting performance within an indoor space constitutes the real challenge when selecting and designing sun breakers in South facing office facades. Further research is directed towards exploring other sun breakers configurations and their efficient combinations.

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# A STUDY OF MULTI-ZONE DAYLIGHT-RESPONSIVE DIMMING SYSTEMS

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Abstract --- Daylight-responsive dimming systems currently considered in scientific research and commercial applications predominantly restrict themselves to the control of a single dimmed zone. This paper explores a multi-zone approach to controlling daylight-responsive dimming circuits. The conceptual basis for a generalized, optimal multi-zone dimming scenario is introduced by building on the concept of conventional single-zone dimming. Performance of an optimized multi-zone dimming system is compared with that of a single zone dimming system in the context of a daylight delivery system with sidelighting. The relevance of the two optimized, multi-zone dimming algorithms created by the authors is discussed with regards to the development of a real-world multi-zone dimming control strategy.

Keywords: Daylighting, lighting control, dimming, multi-zone control

## 1 INTRODUCTION

Currently, there is a broad consensus on the energy-savings potential of daylight-responsive control, however, less than 2 percent of commercial buildings in the U.S. have such a system installed. Data collected from field installations of daylight responsive control systems have often contrasted poorly to the predicted potential of such systems (Williams et al, 2012).

Contemporary research on daylight responsive dimming systems has focused on improving the accuracy of daylight sensing through field tests and performance modeling, optimizing shading control, and the development of improved metrics (Mistrick and Sarkar 2005; Mistrick and Casey 2011; Kim and Song 2007; Seo, Ihm and Krarti 2011; Reinhart, Mardaljevic and Rogers 2006). There have been few attempts to this date to incorporate multi-zone control into daylight responsive dimming systems.

A 9-month monitored study, conducted in 2003 on a building mock-up was one instance where performance of multi-zone systems was studied in a controlled environment (Lee and Selkowitz, 2006). It was observed that in a room lit by a sidelighting system, lighting zones closer to the glazing could be dimmed to a much lower level than the dimmed zone in other parts of the room, providing additional energy savings compared to a system where all the zones were dimmed to the same level. A multi-zone daylight harvesting approach patented by Leviton Manufacturing Co. (Hick and Leinen, 2009) describes a multi-zone closed-loop daylight control system where individual zones are controlled according to a predetermined rate of change within each zone. According to this method, the rate of change for the dimming level within each zone, in relation to a photosensor signal, depends on the proximity of the zone to the window glazing.

This paper describes a study where a first principle based approach was applied to multi-zone daylight responsive dimming systems. Electric power and workplane illuminance equations were used to identify optimum performance conditions for single and multi-zone dimming systems. The optimum conditions were simulated for daylit spaces with unidirectional sidelighting using two different control scenarios. The following sections describe the theoretical basis for optimized multi-zone dimming and its application in developing a multi-zone dimming strategy for real-world spaces with unidirectional sidelighting.

## 2 THEORY

This section discusses the illuminance and electric power relations applicable in the case of photosensor-controlled dimming systems with single and multiple zones. It also describes the theoretical, optimized dimming scenarios that maintain target illuminance on the workplane while consuming the lowest possible electric power.

### 2.1 Single-Zone Dimming: Illuminance and Power Equations

Conventional, single-zone daylight-responsive control algorithms generally utilize a “critical point” approach as a basis for photosensor calibration and control. The critical point on the work-plane is the point that requires the highest setting of the dimmed lighting zone (DiLaura et al, 2011; Mistrick and Sarkar, 2005).

Illuminance at a given point on the work-plane of a room with daylighting and a single-zone dimming system ($E_{Single}$) can be described by equation (1)

$$E_{Single} = E_{Daylight} + E_{Non\text{-}Dim} + E_{Dim} * D_S \qquad (1)$$

where $E_{Single}$ is the total illuminance at the critical point, $E_{Daylight}$ is the illuminance contribution from daylight, $E_{Non\text{-}Dim}$ is the illuminance contribution from the non-dimmed zone, $E_{Dim}$ is the illuminance contribution from the dimmed zone at full output, and $D_S$ is the dimming level of the dimmed zone. Assuming there is negligible lumen depreciation or lamp burnout from the time of calibration, $E_{Non\text{-}Dim}$ and $E_{Dim}$ can be assumed to be constant for the room, while $D_S$ varies inversely to $E_{Daylight,}$ as determined by the control system. Power ($P_{Single}$) consumed by the electrical lighting system can be described by equation (2) as

$$P_{Single} = P_{Non\text{-}Dim} + P_{Dim} \qquad (2)$$

where $P_{Non\text{-}Dim}$ is the power consumed by the non-dimmed zone, $P_{Dim}$ is the power consumed by the dimmed zone. $P_{Dim}$ can be further explained in detail, as shown in equation (3)

$$P_{Dim} = N_{Dim} * (BP_{Min} + ((D_S\text{-}D_{Min})/(D_{Max}\text{-}D_{Min})) * (BP_{Max} - BP_{Min})) \qquad (3)$$

where $N_{Dim}$ is the number of luminaires in the dimmed zone. Minimum and rated power levels consumed by the ballast are $BP_{Min}$ and $BP_{Max}$ respectively. Equation (3) indicates that the dimmed zone, if switched ON and operating at minimum output, would consume a base power of $N_{Dim} * BP_{Min.}$

2.1.1 Single-Zone Dimming: Optimum Condition

Ideally, the critical point is maintained at a target illuminance by the dimming system while other locations on the work-plane have illuminance greater than or equal to the target illuminance. In practice, however, the critical point location is not fixed within a space and varies with daylighting and shading conditions over the course of a day and throughout the year.

If one were to consider a theoretical condition where the real-time position of the critical point is considered in computing dimming levels (i.e., the critical point is permitted to move), then such a scenario represents optimum energy consumption by a single-zone system in maintaining the required work plane illuminance.

## 2.2 Multi-Zone Dimming: Illuminance and Power Equations

Illuminance calculations for a multi-zone dimming system with daylighting are similar to a single-zone system. In essence, the illuminance at any given point is a function of the illuminance contributed by daylight, the non-dimmed zone, and the dimmed zones. Equation (1) can be adapted to describe the illuminance at any point in a multi-zone scenario with N zones as shown in equation (4).

$$E_{Multi} = E_{Daylight} + E_{Non\text{-}Dim} + E_{Dim1} * D_1 + E_{Dim2} * D_2 + E_{Dim3} * D_3 \;\ldots\ldots\ldots + E_{DimM} * D_M \qquad (4)$$

where $E_{Dim1,}$ $E_{Dim2}$ $E_{Dim3}$…. $E_{DimM}$ are illuminance contributions from the dimmed zones at that point and $D_{1,}$ $D_{2,}$ $D_3$ and $D_M$ are dimming levels for Zones 1, 2, 3 and Mth zone respectively.

Similarly, equations (2) and (3) can be adapted to a multi-zone scenario. Power ($P_{Multi}$) consumed by a multi-zone electrical lighting system can be described by equation (5) as

$$P_{Multi} = P_{Non\text{-}Dim} + P_{Dim1} + P_{Dim2} + P_{Dim3} \ldots\ldots\ldots\ldots\ldots\ldots.. + P_{DimM} \qquad (5)$$

Power consumption by individual zones ($P_{Dim1}$, $P_{Dim2,}$ $P_{Dim3}$ ...$P_{DimM}$) can be expanded further as shown in equations (6),(7), (8) and (9)

$$P_{Dim1} = L_{Dim1} * (BP_{Min}+((D_1-D_{Min})/(D_{Max}-D_{Min})*(BP_{Max} - BP_{Min})) \qquad (6)$$

$$P_{Dim1} = L_{Dim2} * (BP_{Min}+((D_2-D_{Min})/(D_{Max}-D_{Min})*(BP_{Max} - BP_{Min})) \qquad (7)$$

$$P_{Dim3} = L_{Dim3} * (BP_{Min}+((D_3-D_{Min})/(D_{Max}-D_{Min})*(BP_{Max} - BP_{Min})) \qquad (8)$$

……………………………

$$P_{DimM} = L_{DimM} * (BP_{Min}+((D_M-D_{Min})/(D_{Max}-D_{Min})*(BP_{Max} - BP_{Min})) \qquad (9)$$

where $L_{Dim1,}$ $L_{Dim2}$, $L_{Dim3}$ and $L_{DimM}$ are the number of luminaires in Zones 1, 2, 3 and M respectively.

2.2.1 Multi-Zone Dimming: Optimum Condition

Considering equation (4), for a given value of $E_{Daylight}$, the illuminance at any point can be changed by varying $D_1$, $D_2$,$D_3$ … $D_M$, either individually or in combination. An optimized condition would be one where the lighting system consumes the least amount of power while maintaining the required illuminance at all required analysis locations. It can be observed from equations (6), (7), (8) and (9) that power consumed by a zone varies directly with its dimming level. Considering equations (4), (5), (6), (7), (8) and (9) it appears that for optimal power consumption, the dimming level of each zone should vary in proportion to the illuminance contribution by that zone at the given point.

Commercially available ballasts tend to have minimum dimming levels that range anywhere from 1% to 20% and have associated minimum power values that can often be over 25% of the rated power of the ballast (Doulos, Tsangrassoulis and Topalis 2008; Philips Lighting Electronics 2012). Therefore, in instances where the minimum power consumption of an electronic ballast represents a significant proportion of its rated load, instead of dimming each of three controlled lighting zones to maintain target illuminance across a space, it might be more economical to turn off one or more zones while increasing the output of another zone to prevent the lighting system from consuming excessive power due to these high power values at minimum output.

## 3 MULTI-ZONE DIMMING: UNIDIRECTIONAL SIDELIGHTING

The performance of single and multi-zone dimming systems under optimized conditions, as discussed in the previous section, was studied by the authors in the context of daylight delivery systems with unidirectional sidelighting. Daylit spaces were simulated using the Daysim daylighting software (Daysim, 2012) and multi-zone optimized dimming was applied by applying an optimized dimming control algorithm. A subsequent, sequentially optimized, dimming algorithm was developed on the basis of the dimming trends observed with the original, multi-zone optimized algorithm.

While multiple spaces with varying dimensions, site-orientations and electric lighting systems were considered for this research, owing to length restrictions, this paper presents a typical example of a room with unidirectional sidelighting and automated shading. The methodology and results explained below conform, in essence, to the results obtained by the authors for various daylighting systems with unidirectional sidelighting and multiple dimmed zones.

### 3.1 Experimental Setup

The software model of the room considered for daylight simulations, shown in Figure 1, was created using AutoCAD 2012. The reflectances of the ceiling, walls and floor were 85%, 65% and 20% respectively. The 5-foot high glazing ran across the width of the room and was located 3 feet above floor level. It had a transmittance of 80%. Shading fabric chosen for glare control was of 10% visible transmittance and 4% openness factor.

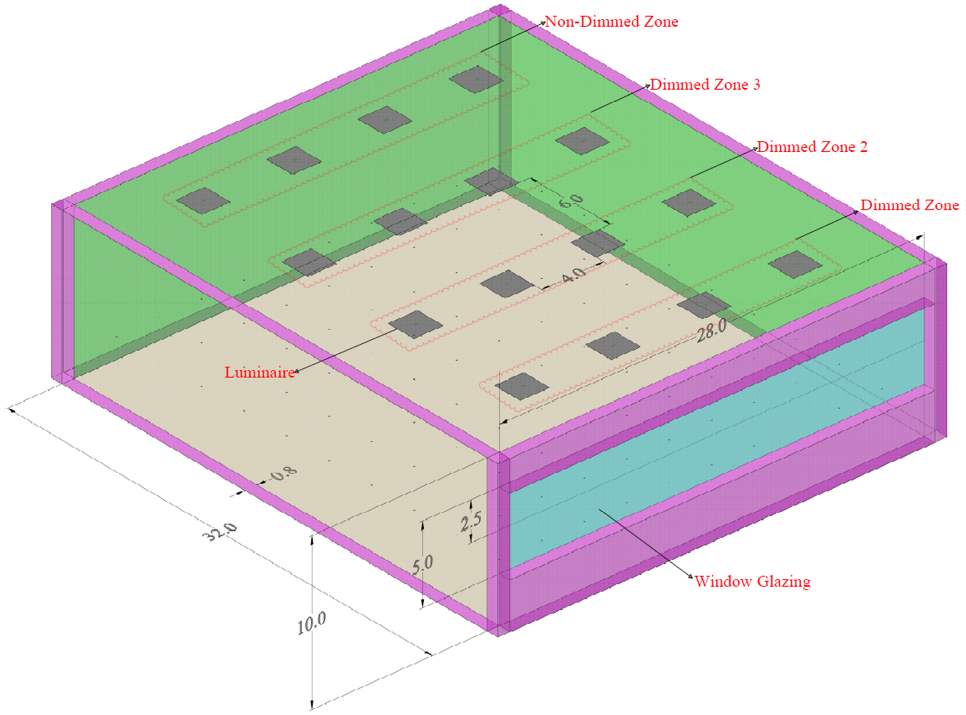


**Figure 1 : Details of the room modeled in this study. All dimensions are in feet.**

The site location, with weather data provided by a WEA climate data file in Daysim, was State College, PA. Ground reflectance of the site was 18%. The study was carried out for a South-facing window orientation . The automated shading system, as managed by Daysim, was controlled by a photosensor mounted on the exterior wall of the room, above the glazing and facing outwards. Shades were lowered to cover half of the window when the solar profile angle dropped below 59° and then lowered to completely cover the window at profile angles below 40°. These angles prevented direct sunlight from striking the work plane at distances greater than 3 feet from the window.

The designed luminaire layout shown in Figure 1, provided an average maintained illuminance of 330 lux, while the control algorithms were programmed to maintain a target illuminance level of 300 lux in accordance with typical office lighting illuminance requirements. The luminaire selected for the lighting system was a 2RT5-14T5, a 2’x2’ troffer from Lithonia Lighting. The dimming ballasts had minimum and maximum dimming levels of 3% and 100% respectively. Power consumed by the ballast ranged from a minimum of 9W to a rated value of 34W. The row (zone) farthest from the glazing was designated as a non-dimmed (always-on) zone and consumed a constant power of 136W. Each of the other three rows was separately controlled in the multi-zone system. The dimmed zone for the single-zone dimming system included the three rows closest to the window (see Figure 1).

### 3.2 Multi-Zone Optimum Control Algorithm (Algorithm O)

A theoretical, optimized multi-zone algorithm (Algorithm O) was designed to consume minimum power while maintaining illuminance of at least 300 lux on all “eligible” work-plane grid points. “Eligible” grid points were those grid points on the work plane where the minimum target illuminance of 300 lux was achievable at 100% light output from all zones during non-daylight conditions.

A control algorithm of this nature is not practically implementable in the field as lighting control systems are usually driven by ceiling-based photosensor input and do not allow for meticulous, real-time, work-plane illuminance readings. The authors felt, however, that an optimum, albeit theoretical, control algorithm would best guide the formulation of any practical control algorithm being considered for an actual installation. Daylight and zonal illuminance data for calculations were collected from output files generated by Daysim. Software code for running the algorithms was written in Visual Basic for Applications (VBA) while the Graphic User Interface (GUI) was created in Microsoft Excel 2010.

Figure 2 shows the variation of zonal dimming levels calculated using Algorithm O. The plots were generated for occupancy hours of 0800 hrs to 1800 hrs for all 365 days of a year using TMY weather data and Perez skies (Reinhart and Herkel 1999). The dimmed zones were switched OFF at times where there was sufficient daylight illuminance on all work plane points. The electric lighting system had power consumption at these conditions of 136W owing to power consumed by the non-dimmed zone. The control algorithm had an error margin of less than 2% in calculating optimum power for a given daylight condition. The zonal dimming trends, as shown in Figure 2, pointed towards an almost sequential order of dimming of lighting zones, with the zone closest to the glazing being dimmed first and being reduced to an output level near 0% before the next zone was dimmed. Similar dimming trends were observed by the authors in simulations conducted for rooms with different dimensions and shading conditions. The optimum control algorithm showed a strong affinity towards sequential dimming of zones instead of simultaneous control of multiple zones.

### 3.3 Multi-Zone Sequentially Optimized Algorithm (Algorithm S)

A multi-zone sequentially optimized control algorithm (Algorithm S) was derived from Algorithm O. This algorithm was programmed to maintain target illuminance across all eligible grid-points at minimum power while dimming the zones in sequential order. For example, with the room and electrical lighting system described in this study, sequential dimming would require Zone 1 to be dimmed to minimum level and turned off before Zone 2 and Zone 3 could be dimmed. Similarly, Zone 2 had to be dimmed to its minimum and turned off before Zone3 could be dimmed.

Figure 3 shows the variation of zonal dimming levels and corresponding power consumption with Algorithm S. It is evident that the plot in Figure 3 shows a very high degree of linearity compared to the plot in Figure 2. This can be attributed to the fact that Algorithm S was designed such that zones would be controlled one after the other, thus preventing the occurrence of any non-linear data points, as seen in regions X and Y of Figure 2. While Algorithm S, in its optimal form (based on a moving critical point), is not practically implementable in a field installation for the same reasons that were outlined for Algorithm O, the concept of dimming zones in sequence should be relatively simple to implement in a real-world dimming system.

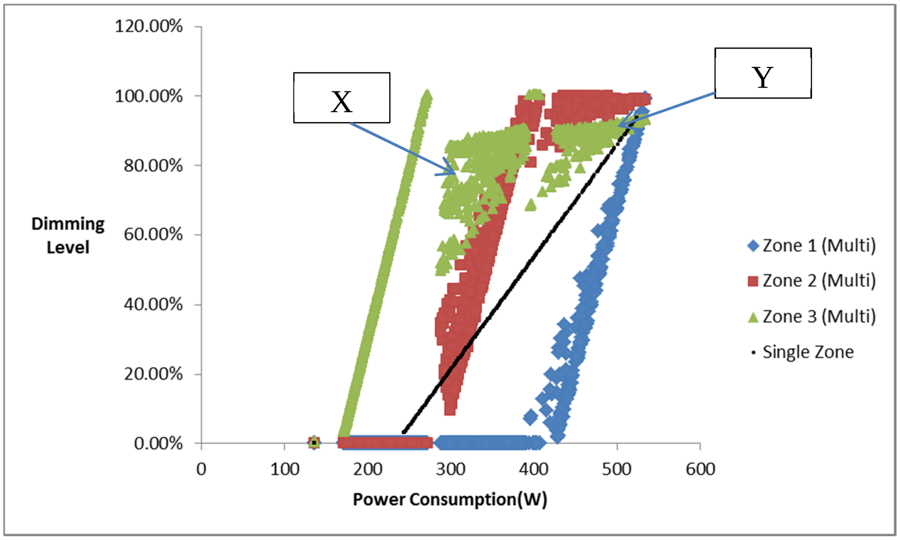


**Figure 2: Variation of zonal dimming values with power consumption for Algorithm O**

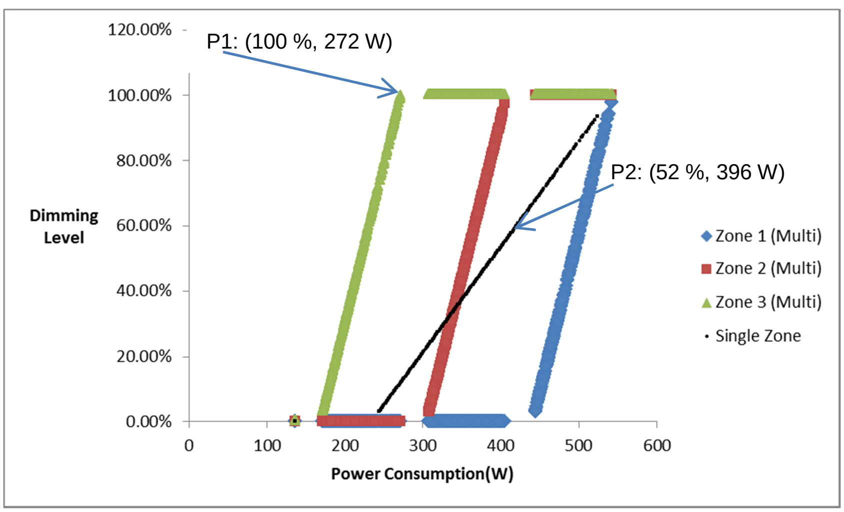


**Figure 3: Variation of zonal dimming values with power consumption for Algorithm S**

## ANALYSIS

A comparison of the excess power consumed by the lighting system controlled by Algorithm S with an identical system controlled by Algorithm O, as shown in Figure 4, indicates that on those occasions when excess power was consumed, the difference in power consumption was not more than 8%. A comparison of annual energy consumption by the three optimized algorithms for North and South orientations of the room is plotted in Figure 5. Data for the North orientation was obtained by orienting the original, South-facing software model towards North and then running the control algorithm. It is

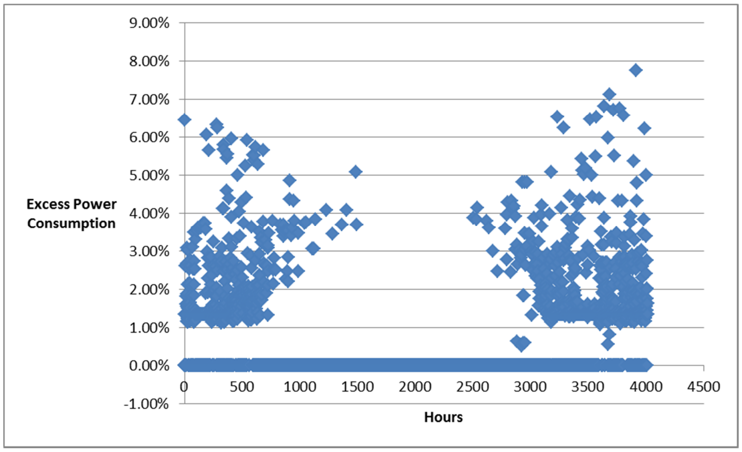


**Figure 4. Power consumed by electrical system controlled by Algorithm S , expressed as a percentage in excess of the power consumed by electrical system controlled by Algorithm O.**

apparent that for both North and South orientations, while there exists a considerable difference in energy consumption between lighting systems controlled through the single-zone and the multi-zone optimized algorithms (Algorithm S and Algorithm O), the difference is negligible when Algorithm S and Algorithm O are compared with each other. These results are significant because they suggest that a daylight responsive multi-zone dimming system, with a control philosophy that simply involves dimming individual zones one after the other, can save up to 15% more energy than a conventional single-zone dimming system when both are optimally controlled. A count of hours for which each zone was dimmed by the single-zone optimized algorithm and multi-zone sequentially optimized algorithm (Algorithm S) is plotted in Figure 6. It shows that, regardless of orientation, the illuminance requirements were met by the Multi-zone algorithm for more than half of the total hours by dimming only a single zone (Zone 3). Points P1 and P2 in Figure 3 show power consumed by the electrical system under such a scenario. While power consumed by a multi-zone system ranges from 172W to 272 Watts, the power consumed a single-zone system under the same daylight conditions ranges from 244W to 396W. Figure 3 also indicates, through a uniform spread of the data-points, that power consumption by the single-zone system is not concentrated at the bottom of the plot, implying that a single-zone system would consume a considerably higher amount of power at any given instance than a multi-zone system.

## CONCLUSION

Results from this study indicate that Multi-Zone dimming systems have the potential to improve the energy performance of conventional daylight responsive dimming systems. While algorithms discussed in this paper were optimized and tested under purely theoretical conditions, the approach to multi-zone dimming described by the authors can be applied to real-world lighting control installations, for dimming as well as switching control. Further research, currently ongoing, on practical implementation of the discussed sequential dimming algorithm has yielded results that correlate well with results obtained for the optimized algorithm. The authors hope to present the results of their progress in the near future.

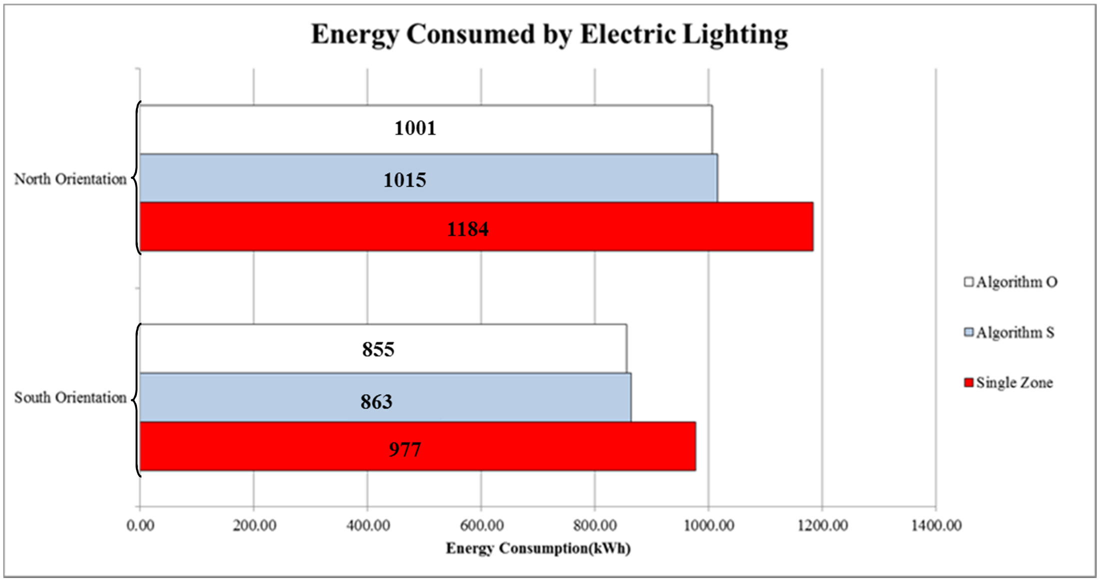


**Figure 5: Energy consumed by the electric lighting system with the optimized algorithms**

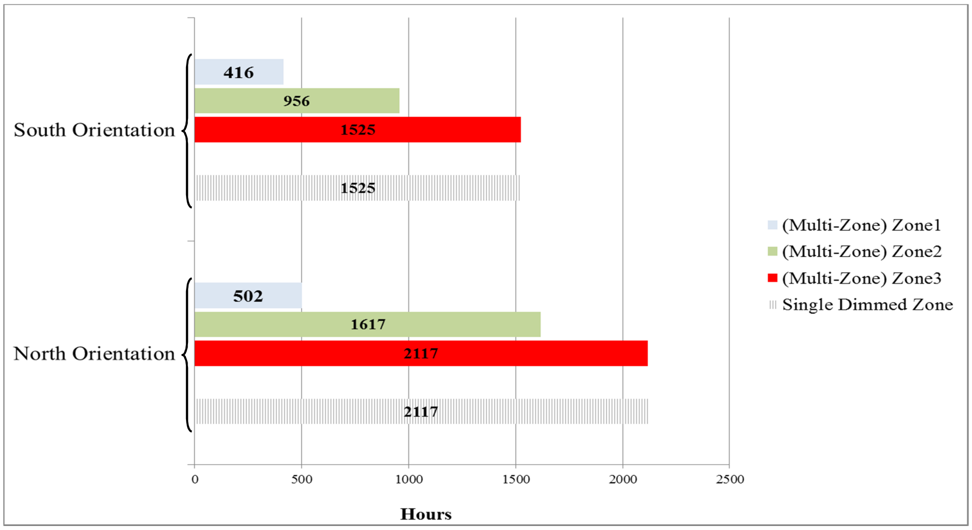


**Figure 6: Number of hours for which each zone is operational annually.**

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# Assessment of the potential savings resulting from shutting down university buildings during periods of very low occupancy: A case study

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## ABSTRACT

Unlike residential buildings, commercial and institutional buildings have a huge diversity of energy end uses and installed capacities. They also have the least amount of measured data available about occupancy profiles. This is especially the case for common university buildings. This reality poses significant challenges to improving their energy performance and informing energy management decisions and policies. University buildings differ from many other types of buildings. Their occupancy profiles have unique features such as extreme low and high occupancy within short periods of time and often very low occupancy in the evenings and during college breaks, weekends, and holidays. In addition to classrooms, these buildings house administrative services, research laboratories, catering, and other activities, meaning that all systems can be operating at full capacity even during low occupancy periods in order to maintain desired thermal comfort levels. This may result in a large consumption of energy per building occupant. Therefore, better space utilization should be a priority if any significant cost savings are to be achieved without any substantial upfront investment.

With the overall target of using Texas A&M University campus in Kingsville, Texas, (TAMUK), as a test bed to examine energy efficiency in university buildings this work reports the results of an initial study of energy usage profiles during very low occupancy periods for a representative building within the TAMUK campus and presents possible solutions to improve energy usage with the potential energy savings. It is believed that the information gathered is of the foremost value to other institutions of higher education sharing similar characteristics and environmental concerns.

**KEYWORDS:** University Buildings, Occupancy Profiles, Energy Efficiency; Energy Savings Potential

## INTRODUCTION

A sensible management of resources is a growing imperative in all economic sectors and particularly in the building sector. The built environment is a major and vital part of any nation's infrastructure and most of the world's people spend the greater proportion of their lives in buildings. Buildings are important consumers of environmental resources, particularly energy. Across the United States, buildings account for nearly 40 percent of all energy and 70 percent of electricity use (source: US Department of Energy). Commercial buildings, in particular, are complex and greatly heterogeneous. In 1995, there were 4,580,000 commercial buildings in the United States representing 60 billion square feet of floor space.

The commercial building sector is dominated by four types of activities: retail and service, office, warehouse and storage, and education. Education buildings account for seven percent of the total commercial buildings in the United States and represent thirteen percent of the total floor space (Diamond, 2001). University campuses belong to this group and are considered major education establishments. Their energy use is often comparable to that of a medium sized town. With thousands of campuses across the United States, these institutions are well positioned to have a significant impact on greenhouse gas emissions simply by making their facilities more energy efficient and sustainable. Additionally, Universities can serve as test sites and models for sustainable practices and societies. Improving the scientific understanding of the broad patterns of energy flows within Universities will help identify areas of high energy consumption where implementing available techniques and technology could significantly save energy and reduce green house emissions.

University buildings differ from other types of buildings, both in design and in the way they are used. They consist of many mixes of building types that serve different functions, such as classrooms, faculty offices, residential halls, dining halls, student union and recreation, power generation facilities, and faculty housing just to name a few of the many possibilities.

## UNIVERSITY ENERGY USE

Every building wastes energy in hundreds or thousands of places. Possible areas for the application of energy-saving measures in university buildings are the building envelope, internal heat gains, such as lighting, equipment and people, and building services, including the HVAC system and domestic hot water. Generally, energy is mostly used for lighting, thermal comfort, equipment, and water heating. Actual energy consumption is affected by a number of fundamental factors including the activities which take place within a building, its built form, the behavior of its occupants, the number of occupants, climate, and other factors.

In a practical university energy conservation program, it is often possible to reduce energy consumption by as much as 20% initially, simply by common sense measures such as ensuring that classroom lights and equipment are turned off when they are not in use. Further conservation measures may require special tuning of HVAC systems or reductions in energy loads, which must usually be done by trained personnel.

Unfortunately, the information and data about university energy use is limited. For example, occupancy schedules are mostly estimates because they are difficult to measure. Apart from dormitories, buildings are generally unoccupied at night, and have very low occupancy over weekends and during long semester breaks. Furthermore, even during term time (semesters), some rooms are irregularly used.

Compounding the problem is the need for HVAC systems to operate at full capacity to ensure the desired comfort and IAQ levels are met during peak demand at full occupancy. In practice, peak demands are usually high and the systems installed are often oversized for periods of low occupancy. Other issue is room ventilation. In university buildings, ventilation is based on peak occupancy; therefore, rooms are over ventilated. Building automation systems can help maintain outside air ventilation rates consistent with actual occupancy through the use of variable speed drives, modulated outside air damper settings and CO2 sensors. Demand control ventilation can result in significant energy savings without degrading occupant comfort. These issues, as well as others, unnecessarily result in large energy consumption, but despite variable periods of high and low demand, there are measures that can be implemented to improve overall energy efficiency of university buildings.

## STUDY INTENT

Due to the number of university buildings and their various functions, this study will specifically focus on a building that houses classrooms, which is a typical representative university building. Classroom buildings usually also include administrative services and research facilities, which are in use all year around. This type of building has a very low occupancy in the evenings, on weekends, and during student breaks, and thus presents a definite potential focus building for energy savings.

A chief interest of this study is load reduction strategies that can be related to extremely low occupancy like reducing HVAC operating hours; maximizing night-time, weekend, and holiday temperature setbacks; turning off unnecessary lights and office equipment; turning off 100% outside air ventilating systems whenever possible, e.g. in research laboratories whenever experiments are not being run or harmful contaminants being released; and shutting down or slowing down related supply fans. However, some of these measures could result in occupant discomfort and should be carefully measured and reviewed by the university administration.

Other strategies - such as changing the location, orientation, or built form - are not feasible, yet significant reductions in energy use can still be achieved without considerable capital investment by identifying what some called the “low hanging fruit." Since universities usually have very limited budgets, any operational savings resulting from the recommended strategies could be used for upkeep, future upgrades, or replacement of other energy inefficient systems, thus resulting in further savings.

This study seeks to analyze data from different sources by investigating occupancy and energy use. Based on the analysis, different strategies will be studied to determine if energy use can be reduced. For example, a potential strategy during periods of high occupancy, such as the fall and spring semester, could be shutting down the building earlier during the week, and shutting down the building on weekends, holidays and other times of very low occupancy. The results will determine from an economic standpoint if a more efficient occupation of the building is justifiable. As an extension of the results, other strategies could be applied to the campus overall. For example, during the summer months, when few students are attending school, dorm residency could be consolidated into as few dorm buildings as possible instead of leaving all dorms operating as if at full capacity. Additionally, all classes could be held in one or two buildings instead of spreading classes all over campus. Unused buildings could then be placed in hibernation mode or completely shut down, which could result in significant cost savings by concentrating energy use to as few buildings as possible.

## PAST RESEARCH

A review of the literature available indicates that very little published work dealt with the occupancy factor as a variable in building energy use (Abushakra, 2001) and even less where occupancy in university buildings was monitored in detail, either in terms of total building occupancy or of individual rooms. However, there have been a larger number of university surveys concerned with the potential for energy savings resulting from buildings shutdown during periods of low occupancy (e.g. West Kentucky University report, “WKU Energy Conservation Shutdown Nets Big Results”, 2009 and Stanford University report, “Most university buildings will shut down during holiday break”, 2003). Unfortunately, reports of these shutdowns do not include any quantitative data on occupancy or hours of very low occupancy.

David et al. (2010) compiled hourly occupancy profile data from different sources, such as building security cameras and doorway electronic counting sensors, for typical occupancy periods. The occupancy building factors for five different classroom buildings show that on weekdays, after 7:00 pm, the occupancy dropped sharply, and from 10:00 pm to 6:00 am there was low to no occupancy in the buildings. On weekends from 8:00 am to 8:00 pm, the maximum occupancy reached was just 2% of the estimated peak occupancy for the buildings. Semester transition weeks are considered in this study as staff occupancy only and vacation periods as considered as zero occupancy.

## THE CASE STUDY BUILDING

The focus of this study is the Engineering Complex, which houses the Frank Dotterweich College of Engineering at the Texas A&M University campus in the city of Kingsville, Texas (TAMUK), located in the most southern region of the state of Texas. The main campus consists of approximately 250 acres and more than 100 buildings with an approximate population of eight thousand people working and living on campus. Many of the buildings share different basic activities like teaching, housing, research and development, administration and student services. Classrooms and laboratories represent roughly 50% of the campus building stock gross area.

The cooling season is hot and humid and lasts for about six months. Cooling demands typically exceed heating needs. Similarly to many educational institutions located throughout the region, the summer peak cooling demand occurs during a period of low occupancy.

The Engineering Complex is 80,418 square feet, consisting of three floors connected by an elevator and staircases in a large atrium. The first floor consists of classrooms, computer labs, laboratories, and a student support room with a study. The second floor contains mostly laboratories, a few classrooms, another computer lab, and faculty offices. The third floor contains the College's administration offices, remaining faculty offices, and faculty lounge. The building is rectangular and L-shaped with the longest end placed on an east-west axis. There are three doors that provide access to the building that can only be entered with a swipe card normal operation hours.

In general the offices administration offices are occupied from 8:00 am to 5:30 pm. Some classrooms are occupied until 9:00 pm for evening lectures. During workdays only authorized people, mostly students, can access the building using their swipe cards after 10:00 pm. On weekends and holidays the building remains locked for 24 hours.

A total of four AHUs serve the entire building. The research laboratories have three fume hood exhaust systems associated with one outside air single duct AHU with a design supply air flow of 13,130CFM. The office and classroom areas are served by three single duct AHUs each on each floor. The three AHUs are associated with four general exhaust systems. The total design supply airflow is 82,605CFM and the total design outside airflow is 35,710CFM. All AHUs are equipped with variable frequency drives (Ayala, 2011).

Several studies have identified and quantified savings resulting from reducing unnecessary electrical loads. The potential savings were for lighting, equipment, and the environmental control system. However none of the studies have looked at the potential savings resulting from shutting down the building and turning off unnecessary equipment. Currently most of the classroom and laboratory spaces are equipped with motion sensors. However there are no sensors in the hallways and faculty or administration offices. Regardless of the occupancy schedules, night surveys found that lights in the hallways, lobby, atrium, and some offices were on 24 hours per day. There are also no night setbacks of air temperature, so the HVAC system operates with the same winter and summer set point temperatures the whole year.

Periods of low occupancy suggest that classroom buildings could be shutdown at earlier hours on weekdays, namely Fridays, and throughout the whole weekend without causing major inconvenience to occupants.

## METHODOLOGY

## Occupancy

Occupancy was assessed for an entire year based on the data collected through different methods. Magnetic Card Readers record the people entering the building when the doors are locked, which is from 10 p.m. to 7 a.m. The doors are automatically unlocked at 7am and people are free to enter and leave as needed. Only people who have access to the building using magnetic cards can enter the building during this time. This data represents non-peak hours when the building is occupied.

Unfortunately the data does not record people exiting the building neither which spaces they occupied. In order to mitigate this shortcoming after hour surveys were performed randomly providing a sense as to who, what, when, and why people are using the building and also justify the magnetic strip count. The data was recorded from approximately 10 p.m. to 12 a.m. Two weekdays and two weekend days were recorded at random.

## Observations

The real time occupancy was not possible to be determined considering the limited means at our disposal. Because the actual balance of people entering and exiting the building could not be determined, in order to determine the occupancy factor it had to be assumed that occupants only stay in the building for a limited time, not longer than an hour. Data analysis revealed that after 12:00 am the building is only randomly occupied. The total number of people entering the building between 10:00 pm and 12:00 am and 8:00 am and 12:00 am on weekdays and weekends, respectively, was averaged over these time periods and also over an estimated peak occupancy of 800 people.

The results show that (Figure 1) that on weekdays and weekends after hours occupancy peaks right before the winter break and also in April, and then declines progressively towards the end of the Spring semester. It keeps at its lowest level during June, July and August. Once classes restart it steadily slopes up again. At any time the maximum occupancy factor barely reaches 1.8 %.

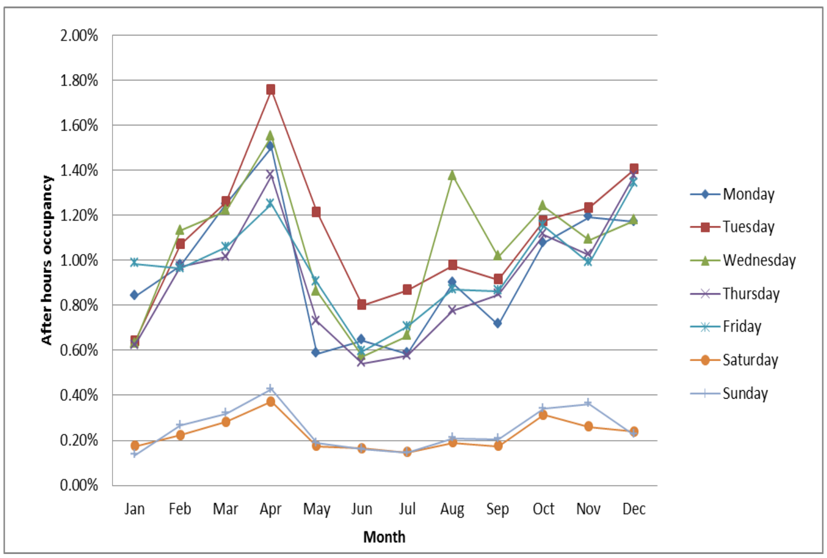


**Figure 1 – After – Hours occupancy factors**

## Estimation of the potential savings

Energy consumption was determined by two methods. First, kWh used by lighting, computers, and other office equipment was calculated. Second, the Support Services, under the Department of Engineering and Planning, collects weekly energy use from sub meters. The calculations and readings were compared to determine their correlation.

## IT and office equipment

Calculating the energy use of computers, monitors, and other office equipment was more challenging due to the various models and pattern of usage. Student computer labs are used at various times during the day, and certain computers are used more often than others due to human behavior. Other office equipment, such as copiers and fax machines, has unpredictable use patterns.

To determine computer and monitor energy use, a representative machine was used to calculate the average wattage consumed. The average wattage was applied to all machines. The use of computers in classrooms was based on the times classes were held in those rooms. The use of computers in student computer labs was calculated by assuming 75% of the computers were in use at all times. The use of computers in faculty offices was based on the average time faculty surveyed stated they worked in their offices during non-class time. The computers and office equipment used by administrative staff were assumed to be on during the normal duty hours of the staff taking into account lunch periods. There is also specialty equipment used in labs such as oscilloscopes, wave generators, power sources, and similar devices. Their use is dependent upon class projects, assignments, and research, and is therefore unpredictable. The energy used by this equipment was not considered.

## Lighting

From a brief observation of the entire building conducted one evening, it was learned that the first and second floor hallway lights in the Engineering Complex are left on twenty-four hours a day. The third floor lights are usually turned off but have been left on for twenty-four hours as well. The security fixtures provide enough lighting in the hallways after hours (after ten pm). The energy consumption of lighting was calculated by multiplying the wattage and number of bulbs in each fixture and the time the fixtures are on. There are over 1200 fixtures.

## HVAC Systems

The savings resulting from shutting off unneeded HVAC operation were estimated based on AHU fan power reduction, terminal box fan power consumption avoidance and AHU Outside Air reduction. They do not account for savings in chilled water.

Table 1 summarizes the estimated dollar savings that could be achieved if these relatively simple measures were implemented.

| Energy Conservation Measure | Annual Cost Savings |
|---|---|
| - Turning off IT equipment | $6,826 |
| - Lights off policy | $2,797 |
| - AHU fan power reduction (weekdays) | $2,249 |
| - AHU fan power reduction (weekends) | $2,698 |
| - AHU OA adjustment to actual occupancy | $20,000 |
| - TB minimum airflow reset | $6,233 |
| **TOTAL** | $40,803 |

**Table 1 – Estimation of savings from turning off or slowing down unnecessary equipment**

## RECOMMENDED STRATEGIES

Based on the results of the current study several strategies should be analyzed:

a) Switching building systems from occupied to unoccupied mode at 10:00 pm
b) Switching building systems from occupied to unoccupied mode at 6:00 pm just for unoccupied zones of the building.
c) Switching building systems from occupied to unoccupied mode at 6:00 pm and throughout weekends and holidays – This scenario requires providing occupants with alternative working stations. If the savings were assumed to be proportional to the avoided operation hours the amount saved yearly would be in excess of $18,000.

All of these scenarios require conducting a more detailed analysis of all evening-time loads to determine which loads can be turned off without inconveniencing students or faculty/staff.

## CONCLUSIONS

This study represents the initial steps towards making the Engineering Complex a more energy efficient building. The measurement of occupancy and energy use of the Engineering Complex should continue and be analyzed to identify the effectiveness of the recommended strategies and to identify other energy use improvements.

Considering that the building studied accounts for just 10% of the total classroom space it is easy to see that if a campus wide shutdown policy was adopted the savings could reach several hundred thousand dollars a year without causing substantial inconvenience to students and staff.

The results of the study can serve as a starting point for energy conservation across the rest of the TAMUK campus as part of the Campus Sustainability Development Plan.

## ACKNOWLEDGEMENTS

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# ANALYSIS OF RESIDENTIAL ENERGY CONSUMPTION CHARACTERISTICS: A COMPARATIVE STUDY BETWEEN TWO CITIES IN CHINA AND THE U.S.

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Abstract

This study compares and analyzes residential energy use patterns of two dominant housing typologies in two sample cities in the U.S. and China (Houston, TX and Xiamen, China). The study developed four residential models to represent single-family-houses and multi-family-houses in both Houston and Xiamen using the building performance simulation tool, eQuest. The parameters of building physical characteristics and occupants' behaviors in these models were based on existing building codes, census data, government surveys, validated previous studies, and a household survey conducted in Xiamen, China. The results of the simulation show the opportunities to increase Chinese residential energy efficiency. The research outcomes indicate that the low energy efficiency of building envelopes and systems in Chinese houses are a major issue in Chinese residential buildings. Avoiding the potential increase in energy use in the Chinese residential sector requires taking steps to improve the efficiency of building envelopes, systems, and appliances. The conclusions of the research provide Chinese energy conservation policy-makers as well as developers and companies with references. The research also provides the foundation for future studies aiming to improve the energy efficiency of Chinese housing.

**Key words:** Comparative study, Residential energy consumption, Sustainability.

## INTRODUCTION

The U.S and China are two of the biggest energy consumers over the world (IEA, 2009). Although, the U.S is currently the top one energy consumer, in the near future China will replace the U.S. becoming the largest energy consumer (EIA, 2010). China's current situation of energy consumption deserves considerably more attention than it has been given.

In China, the residential energy consumption from 1990-2005 represented about 90% of the total building energy consumption, with an annual growth rate of 1.1% (DOE, 2009a, 2009b). However, in China, the researches being conducted in the area of improving residential energy efficiency are not enough to confront the increasing demand of energy, while in the U.S. significant research has already been done in that area. Therefore, comparing residential energy consumption patterns in these two countries will be helpful to overall energy conservation efforts and also be advantageous for Chinese policy makers in the area of residential energy efficiency standards.

## METHODOLOGY

Xiamen in China and Houston in the U.S were selected as the locations of models. They are two similar cities in respects of climate and city size. Some basic information of Xiamen and Houston are shown in Table 1.

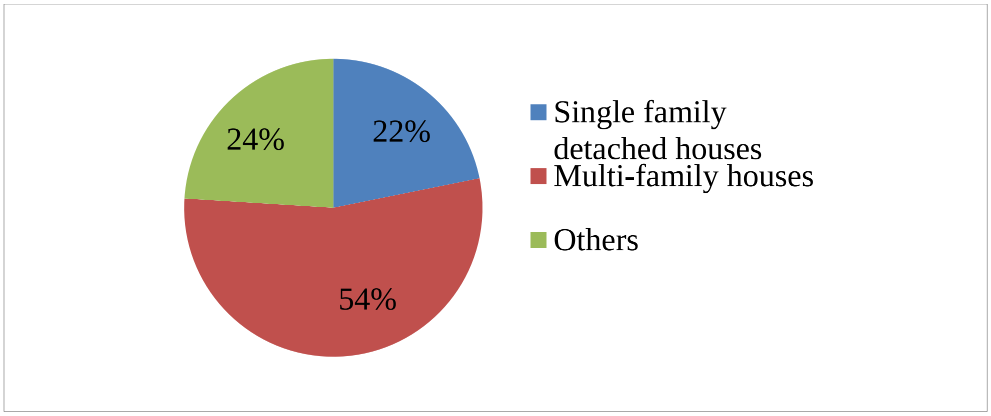
Table 1 City selection parameters

| Factors | | Houston (U.S.) | Xiamen(China) |
|---|---|---|---|
| Geography | | 29°45’46” | 24°26’46” |
| Climate | Zone | humid subtropical (Climate Zone 2) | |
| | Summer (average) | 79.7℉ | 76.3℉ |
| | Winter (average) | 61.3℉ | 63.9℉ |
| Area | | 1,558km$^2$ (656.3 sq mi) | 1,565km$^2$ (604.2 sq mi) |
| Population | | 2,257,926 | 2,520,000 |
| Density | | 1504/ km$^2$(3,897 sq mi) | 1485 / km$^2$ (3,846 sq mi) |
| Source | | *NOAA (2010)*<br>*HKO (2010)*<br>*US Census (2010)* | *China Meteorological Administration (2008)*<br>*Xiamen Municipal Statistic Bureau (2010)* |

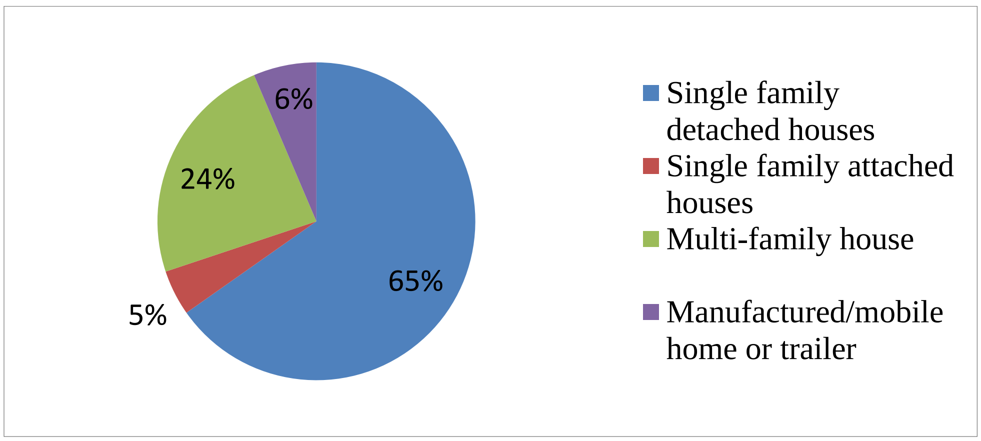
### Typologies of buildings

This research only studies the typical residential buildings. Therefore, before modeling the basic components of the models have to be determined. First of all, residential building patterns are remarkably different between China and the U.S. In previous decades, single-family detached houses were rarely built in China, and in 2006 the government restricted, or did not approve, the development of single-family housing in order to reduce land use waste and to stabilize housing prices (The State Council, 2006). In contrast, in the U.S the single-family detached house is the dominant housing typology. In 2005, single-family detached houses constituted 89% of total floor space of residential buildings in the U.S. (EIA, 2006).

As shown in Figure 1-a, in Xiamen, the dominant housing typology is the multi-family, multi-story residential buildings, which constitutes 65.7% of the total housing . In contrast, single-family detached houses only constitute 24% of the total housing (XUPDI, 2007).




a) Xiamen housing typologies




b) Houston housing typologies

Figure 1 The shares of residential buildings typologies in Xiamen and Houston

As shown in Figure 1-b, in Houston, the single-family detached house is the dominant housing typology. Data provided by the *American Housing Survey for the Houston Metropolitan Area 2007* showed that single family detached houses constitute 62.2% of all housing units, while Houston's multi-family dwellings occupy 33.3% of the total housing units. Single-family detached houses will continue to be in demand in both the U.S. and China because of its advantage in unit size and privacy .

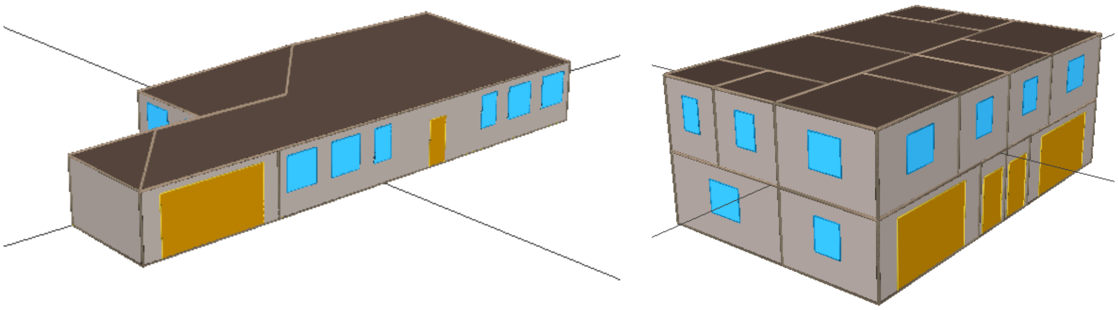
The typical housing typologies in both cities should be compared to each other, but if the single family house in Houston is compared to the multi-family house in Xiamen that is not a fair comparison. To address the problem of the dominant residential housing typologies in the two selected cities, the researcher developed four models that include both single family and multi-family houses in Xiamen and Houston.

**Parameters for models**

Following are four models located in Houston and Xiamen:

1. The Houston Models

Developing the two Houston models (single-family house and multi-family house) was based on existing building energy codes, ASHRAE Standard and baseline models suggested by the U.S. Census Bureau (ASHRAE, 2010; Hendron, 2008, 2010; ICCC, 2009). Detailed inputs and information sources for the two Houston models are presented in Tables 2 and 3, while Figures 2 provides 3-D representation of these models using the



eQUEST software.

Figure 2 Left: A 3-D view of Houston single family house eQuest model.
Right: A 3-D view of Houston multi-family house eQuest model.

Table 2. Design characteristics of Houston single family detached house model

| Input Item | Input Value |
|---|---|
| Floor area | 1964ft$^2$(1674ft$^2$CFA+ 300ft$^2$garage) |
| Building form | Single-story, square |
| Roof surface | Wood Advanced Frame, 24 in.o.c |
| Above grade walls | Wood Frame, 2×4, 16 in. o.c |
| Ceiling U-Factor | 0.035 |
| Frame wall U-Factor | 0.082 |
| Fenestration U-factor | 0.65 |
| Number of bathroom | 2 |
| Number of bedroom | 3 |
| System type | Central Air-conditioning |
| Efficiency | SEER 13 |
| Fuel | Electricity |
| Interior temperature setting | Daytime (°F) 73<br>Night (°F) 75 |
| System type | Furnace |
| Efficiency | AFUE 78% |
| Fuel | Gas |
| Interior temperature setting | Daytime (°F) 69<br>Night (°F) 71 |
| Efficiency | EF=0.594 |
| DHW usage | 60 gallons/day |
| Heat fuel | Gas |

| | |
|---|---|
| Storage capacity | 60 gallon/ day |
| Water temperature | 120 |

| Input Item | Input Value |
|---|---|
| Interior lighting | 0.8*(0.8*FFA+455)= 1621 kWh/yr |
| Exterior lighting | 250 kWh/yr/unit |
| Garage lighting | 100 kWh/yr |
| Exterior lighting | 250 kWh/yr |
| Refrigerator energy use | 669 kWh/yr |
| Washer energy use | 52.5+17.5*BR=105 kWh/yr |
| Dryer energy use | 26.5+8.8* BR=52.9 therms/yr |
| Dishwasher energy use | 103+ 34.3* BR= 205.9 kWh/yr |
| Plug appliances | 1.067 * FFA= 1786.16 kWh/yr |

Table 3. Design characteristics of Houston multi-family dwelling model

| Input Item | Input Value | |
|---|---|---|
| Floor area | 2800ft$^2$(2332ft$^2$CFA+ 468 ft$^2$ garage) | |
| Building form | 2 stories, 2 units, Conventional apartment, square | |
| Envelope characteristics: | | |
| Roof surface | Wood Advanced Frame, 24 in.o.c | |
| Above grade walls | Wood Frame, 2×4, 16 in. o.c | |
| Ceiling U-Factor | 0.035 | |
| Frame wall U-Factor | 0.082 | |
| Fenestration U-factor | 0.65 | |
| Activity area: | | |
| Number of bathroom per unit | 2 | |
| Number of bedroom per unit | 2 | |
| Cooling system: | | |
| System type | Central Air-conditioning | |
| Efficiency | SEER 13 | |
| Fuel | Electricity | |
| Interior temperature setting | Daytime (°F) | 73 |
| | Night (°F) | 75 |
| Heating system: | | |
| System type | Furnace | |
| Efficiency | AFUE 78% | |
| Fuel | Gas | |
| Interior temperature setting | Daytime (°F) | 69 |
| | Night (°F) | 71 |
| Domestic hot water system: | | |
| Efficiency | EF=0.594 | |
| DHW usage | 40 gallons/day/unit | |
| Heat fuel | Gas | |
| Storage capacity | 40 gallon/ day / unit | |
| Water temperature | 120 | |

| | |
|---|---|
| Internal loads: | |
| Interior lighting | 0.8*(FFA*0.542+334)= 874.24 kWh/yr/unit |
| Exterior lighting | FFA*0.145=203 kWh/yr/unit |
| Garage lighting | Garage area*0.08+8= 27.44 kWh/yr/unit |
| Input Item | Input Value |
| Refrigerator energy use | 434 kWh/yr/unit |
| Miscellaneous loads (gas/electric house) | 1595+248*BR+ 0.426*CFA= 2291.65 kWh/yr/unit (electric) 3.7+0.6*BR+0.001*CFA= 0.000000471therms/yr/unit (gas) |
| Cooking loads | 40+13.3*BR=66.6 kWh/yr/unit 14.3+4.8*BR=23.9 therms/yr/unit |
| Washer energy use | 38.8+12.9*BR=64.6 kWh/yr |
| Dryer energy use | 418 + 139* br= 897 kwh/yr/unit |
| Dishwasher energy use | 103+ 34.3* BR= 171.6 kWh/yr/unit |
| Plug appliances | 1.067 * FFA= 1244.122 kWh/yr/unit |

2. The Xiamen Models

Following are the single-family house model and multi-family house model in Xiamen:

As China hasn't have an official report about the baseline model, the author generated the typical single family house and multi-family dwelling in Xiamen based on Chinese buildings codes, official report of residential energy consumption and a reliable survey launched by author herself (CABR, 2003). The survey contains 200 questioners with 42 questions covering five respects of residential basic information, heating and cooling, hot water usage, and home appliances and lighting usage. The detailed characteristics and model inputs of the single-family and multi-family detached houses in Xiamen are shown in Table 4-5 and in a 3-D image of the model as shown in Figure 4.

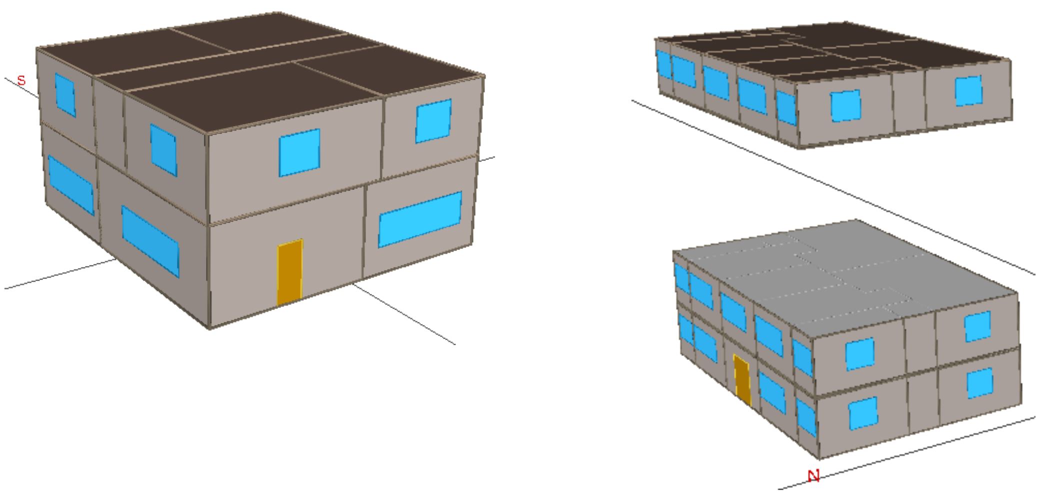



Figure 4 Left: A 3-D view of Xiamen single family house eQuest model.
Right: A 3-D view of Xiamen multi-family house eQuest model.

Table 4 Design Characteristics of Xiamen single family detached house model

| Input Item | Input Value |
|---|---|
| Floor area | 2660 $ft^2$ (2292$ft^2$ CFA +368 $ft^2$garage) |
| Building form | 2 stories, 12 units, square, first floor is public laundry room and storage |
| Roof surface | 4 in Concrete |
| Above grade walls | 8 in. CMU |
| Ceiling U-Factor | 0.088 |
| Frame wall U-Factor | 0.1232 |
| Fenestration U-factor | 0.704 |
| Number of bathroom per unit | 3 |
| Number of bedroom per unit | 4. |
| System type | Split system single zone DX |
| Efficiency | EER 2.7 |
| Fuel | Electricity |
| Interior temperature setting | Daytime (°F) 78.8<br>Night (°F) 80.6 |
| Efficiency | EF=0.6 |
| DHW usage | 2- gallons |
| Heat fuel | Gas |
| Storage capacity | 25 gallon |
| Water temperature | 110 |
| Interior lighting | 0.27w/ $ft^2$ |
| Garage lighting | 0.3 w/$ft^2$ |
| Exterior lighting | 0.0075w/$ft^2$ |
| Refrigerator energy use | 135 w/unit |
| Washer energy use | 1000w/unit |
| Plug appliances | 800w/unit |

Table 5 Design Characteristics of Xiamen single family detached house model

| Input Item | Input Value |
|---|---|
| Floor area | 10800$ft^2$(9540$ft^2$CFA+ 1260 $ft^2$stair and elevator) |
| Building form | 6 stories, 12 units, square, two units per floor |
| Roof surface | 4 in Concrete |
| Above grade walls | 12 in. CMU |
| Ceiling U-Factor | 0.088 |
| Frame wall U-Factor | 0.1232 |
| Fenestration U-factor | 0.704 |
| Number of bathroom per unit | 1 |
| Number of bedroom per unit | 2 |
| System type | Split system single zone DX |
| Efficiency | EER 2.7 |
| Fuel | Electricity |
| Interior temperature setting | Daytime (°F) 78.8<br>Night (°F) 80.6 |
| System type | Electric resistance |

| | | |
|---|---|---|
| Efficiency | EER 1.5 | |
| Input Item | Input Value | |
| Fuel | Electricity | |
| Interior temperature setting | Daytime (°F) | 68 |
| | Night (°F) | 64 |
| Efficiency | EF=0.6 | |
| DHW usage | 20 gallons/day/unit | |
| Heat fuel | Gas | |
| Storage capacity | 25 gallon/ day / unit | |
| Water temperature | 110 | |
| Interior lighting | 0.27w/ $ft^2$ | |
| Corridor lighting | 0.29 w/$ft^2$ | |
| Exterior lighting | 0.0075w/$ft^2$ | |
| Refrigerator energy use | 75 w/unit | |
| Washer energy use | 500w/unit | |
| Plug appliances | 700w/unit | |

## RESULTS AND ANALYSIS

The results were calibrated before analysis. For the models in Houston, the results of the simulations were compared to, and found to be in general agreement with, the RECS（2005) energy use values. The total annual energy consumption of the models was about ±10% from that of the Residential Energy Consumption Surveys (RECS) values. For Chinese models, because of the lack of official baseline models, the researcher utilized indirect data and information to verify the outcomes. The indirect data source for calibrations are local average utility payment and predicted energy consumption provided in the appendix of building codes . Overall, the errors are all in the range of 10% that the simulation results are reliable and could be used for analysis.

The comparison utilizes a number of performance metrics including Annual Energy Use per square foot (also known as Energy Use Intensity or EUI), annual energy use per capita, and annual energy use per household. Each metric is useful for comparison from different angles and guarantees that this comparison is reliable. Figure 5 shows the differences of the energy consumption between the two residential typologies in Houston and Xiamen based on each of these three metrics.

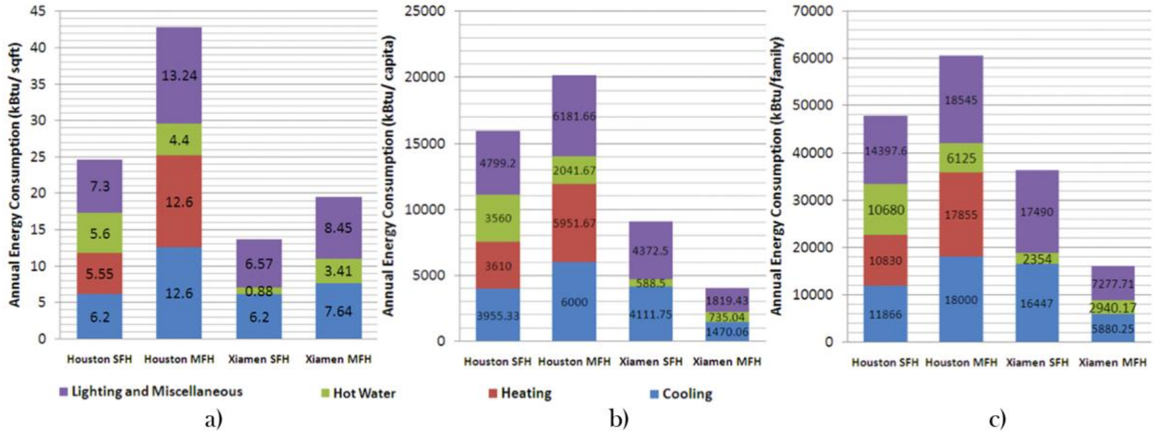



Figure 5 a) Annual energy consumption per square foot of models in Houston and Xiamen

Compare Houston SFH to Xiamen SFH, and then compare Houston MFH to Xiamen MFH, we can find that in general American consume more energy than Chinese in any metric. As shown in Figure 5-a, the EUI of the Xiamen SFH is about 55% less than that of the Houston SFH. Having no space heating is a major reason for the lower energy consumption. Although they located in the same climate zone, Xiamen does not require a heating system . For cooling, the energy consumption per square foot of the Xiamen SFH is the same as the Houston SFH. Otherwise, as shown in figure 5-b and -c, the cooling energy consumption per family and per capita in Xiamen is larger than that in Houston. This was unexpected, because in Houston people use central air-conditioning throughout the whole house, but as shown in the survey, only one to three rooms are air-conditioned in a single-family house in Xiamen. This means the cooled space in Xiamen is smaller than that in Houston but consumes more energy than Houston single-family house, which is an unusual phenomenon. The author listed three possible reasons for this situation: 1) Cooling system efficiency, 2) building envelopes efficiency, and 3) household user behavior. In regard to the efficiency of the cooling system, in Houston it is SEER 13, but in Xiamen, the efficiency factor is about SEER 7.5. Therefore, one reason for the difference should be that the cooling system of Xiamen is less efficient than that of Houston. Another possible reason for this simulation outcome may be the differences of building envelope characteristics (mainly levels of insulation). Based on some Chinese scholars' researches, Chinese buildings' heat transfer coefficient of exterior walls are 3.5 to 4.5 times greater than those of developed countries, 2 to 3 times greater for windows, and 3 to 6 times greater for air leakage (Chen, et al., 2004; Duan, 2000). It confirms the hypothesis that even though there are less air-conditioned rooms in Xiamen residential buildings, the cooling consumption could be more than that of Houston because of less efficient insulation. The third possible reason is that Xiamen residents' behavior of cooling use is wasteful. However, based on the survey of household behaviors, that reasoning is not reliable. First of all, Xiamen residents set cooling temperature 5 °F lower than Houston residents do. Secondly, the duration of operating cooling systems reported by residents in Xiamen is smaller than in Houston.

Hot water is another end use that shows a big gap between Houston SFH and Xiamen SFH. Figure 5-a shows that hot water energy use intensity in Houston is about 6 times greater than that of Xiamen. Figures 5-b and -c, which present the hot water energy use per capita and per family, show that hot water energy us in Houston is more than

Xiamen. Because of the family sizes of the Houston model and Xiamen model are different, the hot water energy consumption per family will not be considered. Figure 5-b shows that the annual energy consumption of hot water per capita in Houston is 6 times greater than that of Xiamen. Different household user behavior should be the main reason for Xiamen's lower amount of hot water use because the hot water use is mainly determined by household behaviors. Possible reasons for the difference in hot water energy use include: 1) in the U.S., almost all the shower and sink water can be ducted from the domestic hot water, but in China, that is not very common. Based on the author's survey, in single family detached houses, 42% of families in Xiamen have only one sanitary unit served by hot water, the bathroom shower. Secondly, the survey shows that 98% of Xiamen families do not have dishwashers and this decreases hot water use (DOE, 2000; J. Li, 2008).

For lighting and miscellaneous energy use, Figure 5-a demonstrates that lighting and home appliance energy consumption of SFH in Xiamen is about 36% less than that of Houston per square foot. Figures 5-b and -c show 29% less per capita and 21% more per family. Since the size of Xiamen single family houses are bigger than those in Houston, the data of energy consumption per family cannot be used to judge which houses are saving energy. In regard to Figure 5-a and -b, the differences probably result from the residents of Xiamen single family houses who have the lower domestic equipment density of area and capita. Figure 5-c shows that the lighting and miscellaneous energy consumption of Xiamen SFH is larger than Houston SFH and is due to a larger floor plan. Additionally, some typical home appliances in China and the U.S. are different. For example, most Chinese people in China do not have clothes dryers that consume a lot of energy, yet clothes dryers are very common in the U.S. Almost all Chinese families use rice cookers frequently, however, they do not usually use coffee makers like Americans do. American families often use dishwashers, but they rarely appear in Chinese households (Parker, Fairey, & Hendron, 2010). Those are all possible reasons to make the energy consumption of miscellaneous appliances different between China and the U.S. The multi-family house comparison is quite similar to the single-family one, so it won't be stated again.

## CONCLUSIONS

With the results of the simulations and the data analysis, the following could be concluded:

1. Houston residential buildings consume more energy than Xiamen, but they are considerably more efficient. In regards to air-conditioning energy consumption, although Chinese residential buildings consume less energy, the thermal characteristics of their building envelopes, as determined by the building codes, are worse than those of American residential buildings. This is more evident in wall insulation, glazing, and air leakage. Therefore, in terms of physical characteristics, Xiamen residential buildings need to improve their building codes in order to improve the thermal resistance of their building envelopes.

2. Regarding the cooling and heating systems and devices, Houston households are also more energy efficient. The energy efficiency of the cooling systems in Houston is SEER 13, but in Xiamen it is only SEER 7.5 (in the building codes it is EER 2.7). For

heating, in the same climate zone, climate 2, the residential buildings in Houston households use heating systems, but Xiamen households rarely do. This is a significant reason for the difference in energy use between the two cities. It is possible that, with the development of the Chinese economy, Xiamen households' quality-of-living will be enhanced making it possible to install heating systems for winter use, as well as whole building HVAC systems. This may happen in some other climate zones in China, thus providing considerable potential for Chinese residential energy use to increase and exceed that of the U.S. in the future. Therefore, there is a need for using high efficiency cooling and heating systems in Chinese residential buildings to improve residential energy efficiency.

3. In regards to household user behaviors, compared to Houston residents, Xiamen residents have more energy-saving behaviors. The most significant of those is the indoor temperature setting where Xiamen residences set indoor temperatures 5℉ higher than Houston residences during the summer. In regard to lighting and miscellaneous energy use, Houston residents have more home appliances than Xiamen residents, and the length and frequency of their operation in Houston families are longer and higher than Xiamen. Finally, regarding hot water use, Houston households use hot water more frequently because of more home appliance needing hot water, such as dishwashers and sinks.

4. As demonstrated in this research, multi-family house in Xiamen consume less energy than single family house per square foot, per capita and per household. In China, both single family houses and multi-family houses are growing in number. In general, these two types of residential buildings will not decrease in the near future, but the share of multi-family dwellings should be larger than that of single family houses because of the policy of restricting single family house development. Therefore, the policy of restricting single family housing is reasonable and will help mitigate the expected energy increases in this sector.

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# Energy Efficiency of External Perforated Window Solar Screens in Desert Environments: Effect of Screen Surface Reflectance

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## ABSTRACT

In hot-arid desert environments, solar radiation passing through windows increases buildings energy consumption. Shading of windows can reduce these loads. Previous research proved that external deep perforated solar screens can achieve up to 30% energy savings. Solar screen colors should be taken into consideration as the lighter the color, the more transmitted proportion of radiation due to increased reflectance, hence affecting daylighting and buildings thermal performance.

This paper investigated the influence of surface reflectance on the energy saving capacity of solar screens in the hot arid desert environment. The relation between screen surface reflectance and other configuration parameters was examined. Series of experiments were performed using the EnergyPlus simulation software for a range of solar screen colors ranging from white screens having a visible reflectance of one, to black screens with a visible reflectance of zero. Simulations were conducted for a screen fixed in front of a window of a typical residential living room space in the Kharga Oasis, located in the Egyptian desert.

It was found that light colored screens reduce lighting and heating energy. However, they significantly increase the cooling energy, and thus overall energy consumption. Results scientifically confirm the effectiveness of the traditionally used colors of the old “Mashrabeya” solar screens, which were typically dark. Conclusions prove that screens visible reflectance could reduce energy savings up to 14%. Optimum ranges of screen visible reflectance were recommended.

**Keywords:** Solar Screen; Visible reflectance; Desert buildings; Shading; Window; Energy; Egypt.

## INTRODUCTION

Traditionally, perforated wooden solar screens were used for shading the openings of the Middle-Eastern desert buildings. They were widely used as climate control devices, where they controlled the penetration of the harsh desert solar rays into building spaces. Dark colored screens with low perforation and depth rates were specifically typically used in the residential spaces (Figure 1). Solar screens can be used to decrease the cooling, heating and lighting energy loads, while reducing visual and thermal discomfort. For optimal energy performance and overheating prevention, the beam solar radiation transmitted through window screens should be controlled during the overheated time periods. External solar screening can block the high incidence angle beam radiation before it reaches the façade, while allowing vision and adequate daylighting.

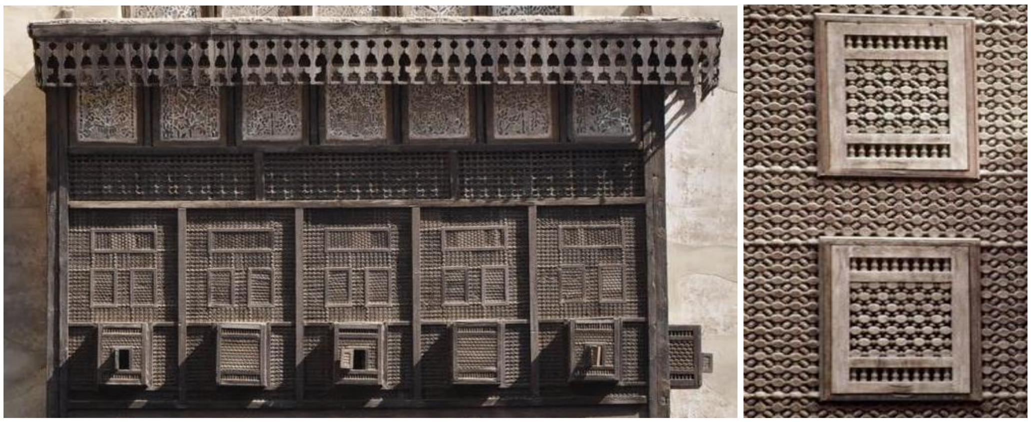

Figure 1: Traditional screens of low perforation percentage, depth and reflectivity.
(The story of my life. N.p., n.d. Web. 10 Mar. 2011. <http://onemilegrads.blogspot.com/2010_08_01_archive.html)

The revival of traditional solar screens in new modern forms may help reduce the energy consumption of new as well as existing buildings. Modern forms of screens are simply perforated without the sophisticated lattice work. Modern screens can be made of different materials for example movable metals. In this research, simply perforated modern wooden solar screens configurations will be investigated.

The effect of solar screen configurations on energy loads was studied in small number of recent publications. This included the effect of using external perforated solar screens on Window-to-Wall Ratios. It was found that optimum WWR for un-screened windows in the severe desert environment of Kharga Oasis was 4% for orientations of South, west, and east, while in north the optimum was a range between 4%-8%. The energy consumption of the 4% unshaded window was achieved with a medium sized window of 22%WWR when screens were used (Sherif et al., 2011).

Other forms of solar shading systems were examined in different studies. Utilization of external fine cable structures as a shading system was found to reduce cooling loads and preserve privacy at the same time. It was found that savings reached 50 to 60% by decreasing the spacing between the cables ten times (Hatice and Raymond, 2008). The shading effect and heat gain reduction of several window treatment approaches as window tinting, reflective window films, shading screens, awnings, and overhangs were examined in various cities in Florida. It was found that changing the orientation slightly affected the shading amount. This was attributed to the high average diffuse radiation component. However, changing the location varied significantly (Ross and Chandra, 1984).

The effect of solar screen surface reflectivity on energy consumption was seldom addressed in recent literature, especially in the hot-arid desert climate. Moreover, understanding of the interaction between surface reflectivity and other important screen configuration parameters, such as screen perforation and depth is missing. These factors must be taken into consideration when designing these shading devices in desert buildings, as the more reflective the solar screen, i.e., lighter the color, the more transmitted solar radiation affecting thermal loads.

## OBJECTIVE

The aim of this paper was to quantitatively investigate the influence of changing solar screen surface reflectivity on the total annual energy load of residential desert buildings. Since this factor cannot be examined in isolation from its interaction with other screen configuration parameters, it was addressed in relation to the most effective ones: screen perforation and depth. The ultimate goal was to provide a better understanding of the factors affecting the performance of solar screens in the harsh desert, thus helping in reaching modern configuration for today's environment.

## METHODOLOGY

A range of screen surface colors was examined in all orientations. They ranged from dark colored screens having visible reflectance of zero, to light colored ones with visible reflectance of one. Two extreme screen configurations were selected for modeling. These were: a tight screen having 40% perforations with depth ratios of 0.5 and 1, and an open screen with large openings having an 80% perforation rate and a depth ratio of one. The research focused on these specific parameters to conduct a comparison between the performance of light traditional dark screens with low perforations and the deep modern light colored ones with wide perforations. Screens with 40% perforation, depth 0.5 and reflectivity of 1 allow a significant proportion of the solar radiation to be transmitted by reflection into the space. On the other hand, screens with 80% perforation, depth 1 and reflectivity of 1 allow less solar radiation to be reflected inside the space since some were absorbed or blocked by the deep screen. This is illustrated in Figures (2 and 3).

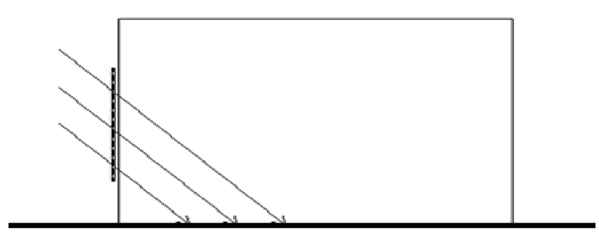

Figure 2: Solar reflectance on a screen with 40% perforation, depth 0.5 and reflectivity of 1.

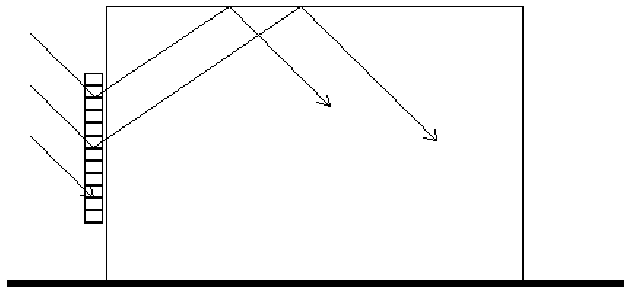

Figure 3: Solar reflectance on a screen with 80% perforation, depth and reflectivity of 1.

A hypothetical residential dwelling lounge was used as a test space. Specific input building parameters were chosen to suit the desert environment and were as follows: a living room isolated from the external environmental thermal changes by assuming that all surfaces, other than the external tested wall, were adiabatic. Thus, three walls, floor and roof were assumed adiabatic. The fourth wall was defined as a double brick insulated cavity wall with a U- value of 0.475 W/m² –k that carried a window at its centre. The Window to Wall Ratio was assumed to be 20%. The solar screen was externally mounted at a distance of 50mm from the wall. Description of the tested space and screens parameters is provided in Tables (1 and 2).

Table 1: Dimensions and parameters of the tested dwelling lounge

| **Dwelling Lounge Space Parameters** | |
|---|---|
| Floor level | Zero level |
| Dimensions | 4.20 m * 5.40 m * 3.30 m |
| Wall Thickness | 0.35 m |
| **Window Parameters** | |
| Dimensions | 2.30 m * 1.20 m |
| Sill Height | 1.0 m |
| WWR | 20% |
| Material | generic double clear glazed separated by 13mm air gap |

Table 2: Dimensions and key variables of the tested screen

| **Solar Screen Parameters** | |
|---|---|
| Dimensions | 2.70 m * 1.80 m |
| Material | Brown matt painted Oakwood |
| Position | Externally mounted at 50 mm from the wall |
| Shape | Orthogonal grid of rectangular section bars of spacing 0.15 m |
| Reflectance | Zero to 1 |
| Perforation % | 40 and 80% perforations |
| Depth Ratio | 0.5 and 1 |

Computer simulation was performed using the EnergyPlus software. The main focus of the simulation was to evaluate the effect of alternative configurations on energy demand in the terms of cooling, heating and lighting loads. Testing was performed using the weather data of the severe hot arid desert environment of El-Kharga Oasis, Egypt, located in the African Sahara. This location has mean daily maximum reaching 40°C during summer months, extreme maximum reaching 50°C and mean daily minimum of 6°C in January, but in extreme cases goes down to zero. Annual simulation runs were conducted for the main four orientations (N., E., S. and W.) using typical meteorological year (TMY) weather data of Kharga (25°N-28°E). A split unit type air conditioning system was assumed. The heating and cooling set points were 23 ˚C. The heating supply air temperature was 35 ˚C. The cooling supply air temperature was 12 ˚C. Artificial lighting was set to be dynamically controlled by sensors according to daylighting adequacy. A Daylighting control was set up with an illuminance set point of 300 lux at the centre of the dwelling lounge. The internal occupants' load was accounted for, while the energy consumption of appliances was not considered.

The annual energy consumption of a base case was calculated first. It was a residential lounge of the above descriptions with a screen of a dark color (zero reflectance). Then, several screen configurations with reflectance ranging from zero to one were compared to the base case.

## RESULTS AND DISCUSSION

**Screen Surface Reflectivity and Depth**
For screens having a 40% perforation rate and a depth ratio of 0.5, the sum of the annual energy loads gradually increased with the increase of screen reflectivity from zero to one with a maximum of 141.5 kwh/m² (Figure 4).

When taking a closer look at the results, it can be observed that in the West orientation, cooling energy increased with the increase in solar screen reflectivity, reaching 8% compared to screens with dark or zero reflectance. On the other hand, the lighting energy load decreased with the increase of screen reflectivity by only 2%, as dependence on artificial lighting decreased, where highly reflective screens increased daylighting of the indoor space. The heating load was almost negligible and constant since simulations were performed in extreme desert environment. A similar performance was observed in the East orientation. For the South orientation, the lighting electricity decreased with the increase in solar screen reflectivity at higher rates, reaching 8% compared to screens with dark or zero reflectance, while the change in cooling energy resulting from the increase in solar screen reflectivity was insignificant (<1%). Thus, high reflectivity slightly enhanced the energy savings in the South orientation. In the North orientation, by increasing the screen reflectivity from zero to 1, the lighting electricity was reduced by 9%, while the cooling loads were increased by 16%. Increasing the screen reflectivity decreased the overall energy savings resulting from the use of screens. The reason of this phenomenon could be attributed to the absence of direct solar exposure onto the screen, which made the screen act as a dimming device, rather than a tool for solar control.

When increasing the depth ratio from 0.5 to 1 (for a 40% perforated screen), the energy performance resulting from use of dark colored deep screens was enhanced. Thus, the maximum energy loads reached 137 kwh/m².

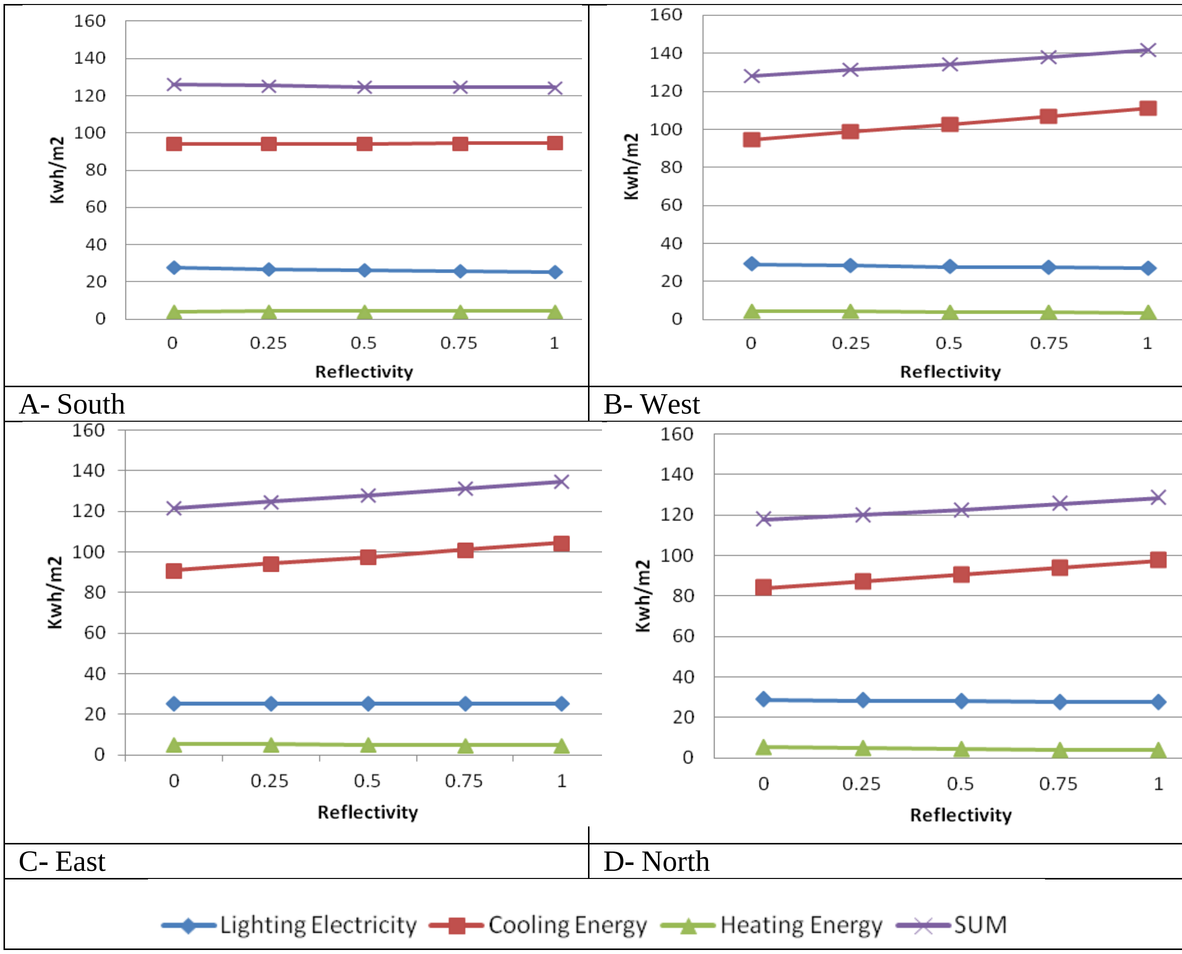


Figure 4: Annual Energy Consumption using Solar Screen 40% perforation and depth 0.5

The daylighting improved significantly. For example, in the West, light colored solar screens with high visible reflectance of 1, reduced lighting electricity by 13% compared to screens with dark or zero reflectance. On the other hand, cooling energy increased by 18% causing the overall energy consumption to increase reaching 9%. This could be attributed to the severe climate of Egyptian desert environments, where the cooling loads were the dominant loads followed by the lighting electricity, which represented almost 15% of the total energy loads. The heating loads were almost negligible. The East orientation had a similar behavior. In the South, screens with reflectivity of 0.25 and 0.5 reduced the energy consumption values. Then it started to increase again at reflectivity of 0.75 and 1. Light colored solar screens with high visible reflectance of 1 reduced lighting electricity and cooling energy to 9% and 1% respectively compared with screens with dark or zero reflectance. In the North, light colored solar screens with high visible reflectance of 1 reduced lighting electricity by 7% compared to screens with dark or zero reflectance. On the other hand, cooling energy increased with 17% leading to the increase in the overall energy consumption (Figure 5).

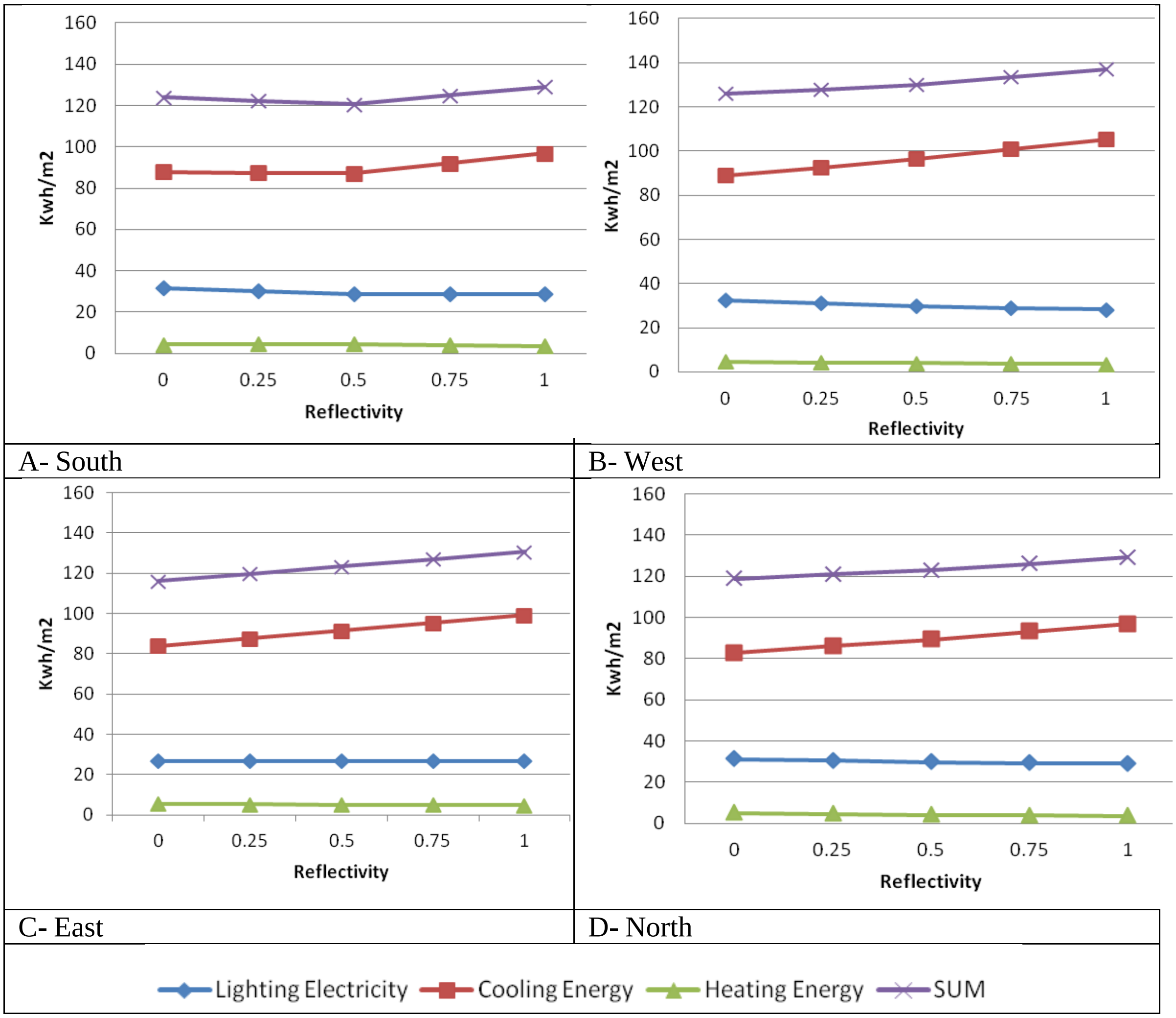


Figure 5: Annual Energy Consumption using Solar Screen 40% perforation and depth 1

**Screen Surface Reflectivity and Perforation Percentage**

The energy performance resulting from use of dark colored screens was significantly improved as a result of increasing the screen perforation percentage from 40% to 80%, at a constant depth ratio of 1 (Figure 6). Thus, the maximum energy loads reached 128kwh/m². The deep screen of wide openings blocked and absorbed the solar radiation, while allowing more daylighting inside the space.

In the West orientation, light colored solar screens having high visible reflectance of 1 reduced the savings in lighting electricity by 2% compared with screens with dark or zero reflectance. On the other hand, cooling energy increased by 20%. In the South orientation, light colored solar screens with high visible reflectance of 1 reduced the savings in lighting electricity by 3% compared with screens with dark or zero reflectance, while cooling energy increased by 20%. In the East orientation, light colored solar screens with high visible reflectance of 1 reduced the savings in lighting electricity by 1%, while it increased the cooling energy by 21% compared with screens with dark or zero reflectance. In the North orientation, light colored solar screens with high visible reflectance of 1 reduced the savings in lighting electricity by 1%, while it increased the cooling energy by 20% compared with screens with dark or zero reflectance.

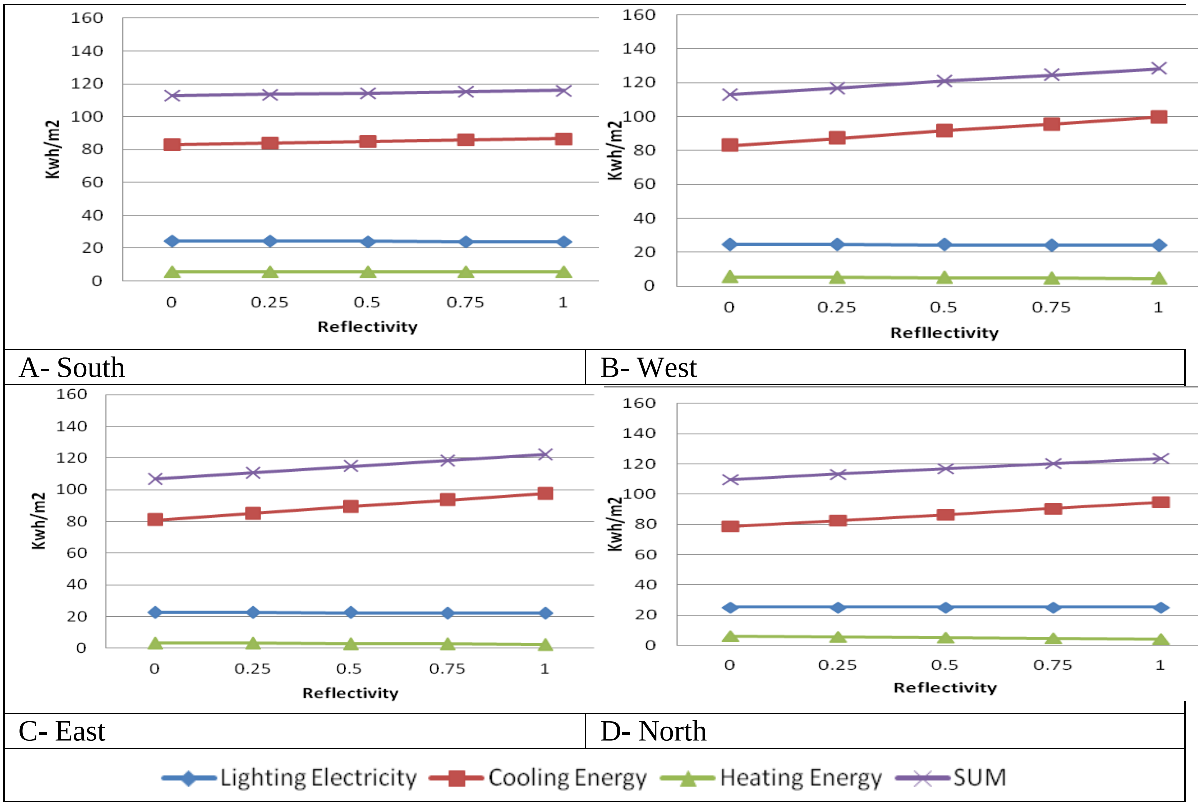


Figure 6: Annual energy consumption using solar screen 80% perforation and depth 1

## Overall Energy Savings

The total annual energy savings resulting from use of solar screens with different reflectivity values in all orientations in comparison with dark screens of zero visible reflectance were summarized in the following tables. The energy savings resulting from use of dark colored 40% perforated screens with depth ratio of 0.5 in the West, East, South, and North orientations (Tables 3 and 4). It was observed that for the 40% perforated screen, increasing the screen depth from 0.5 to 1 slightly enhanced the energy savings achieved by the use of screen in the West. This could be due to the increase in the depth of the dark screen that absorbed more portion of solar radiation. While, in the South, screens with 40% perforation and depth ratio of 1with 0.25 and 0.25 visible reflectance outperformed the screen of 40% perforation , depth ratio of 1with zero visible reflectance by up to 3%.

For the screen of wider openings (80% perforations) and depth ratio of 1, increasing the reflectance lead to a more significant increase in the total energy loads up to 14% compared to the dark screen of zero reflectance. This could be due to the considerable portion of reflected solar radiation out of this highly perforated screen (Table 5).

Table 3: Energy Savings by using Screen with **40% perforation and depth ratio of 0.5**

| Reflectivity | 0 | 0.25 | 0.5 | 0.75 | 1 |
|---|---|---|---|---|---|
| West | 0% | 2% | 5% | 8% | 10% |
| East | 0% | 3% | 5% | 8% | 11% |
| South | 0% | 1% | 1% | 1% | 1% |
| North | 0% | 2% | 4% | 7% | 9% |

Table 4: Energy Savings by using Screen with **40% perforation and depth ratio of 1**

| Reflectivity | 0 | 0.25 | 0.5 | 0.75 | 1 |
|---|---|---|---|---|---|
| West | 0% | 2% | 3% | 6% | 9% |
| East | 0% | 3% | 6% | 9% | 13% |
| South | 0% | -1% | -3% | 1% | 4% |
| North | 0% | 2% | 4% | 6% | 9% |

Table 5: Energy Savings by using Screen with **80% perforation and depth ratio of 1**

| Reflectivity | 0 | 0.25 | 0.5 | 0.75 | 1 |
|---|---|---|---|---|---|
| West | 0% | 4% | 7% | 10% | 14% |
| East | 0% | 4% | 8% | 11% | 14% |
| South | 0% | 1% | 1% | 2% | 3% |
| North | 0% | 3% | 6% | 10% | 13% |

These results concur with previous research results which demonstrated that dark colored screen with 30% perforation and 0.5 depth ratio (similar to the traditional Mashrabeya) could achieve savings up to 21%, 17%, 21% in the West, East and South orientations respectively. In the North, use of these screens has led to a negative impact by increasing the energy loads by 5% (Sherif et al., 2012). To achieve the same energy savings by using modern light colored screens, an 80% perforated screen with depth ratio of 1 and visible reflectance of 0.75 could be used in the West. Decreasing the visible reflectance to 0.25 can achieve similar savings in the East. However, if these modern screens were used in the North with visible reflectance less than 1, energy savings up to 7% could be achieved. On the other hand, in the South orientation using modern light colored screens with visible reflectance of 1 will exceed the energy savings of the traditional screen by 6%.

**Effect of Monthly Cooling Energy on Screen performance**

The summer cooling energy loads represent the highest factor affecting the total increase in energy consumption due to the harsh desert environmental conditions of the Kharga oasis. Figure (7) illustrates the monthly cooling energy loads for a dark screen with zero reflectance and an almost white screen with reflectance of 1 in the south with 80% perforations and depth ratio of 1. Use of dark solar screens reduced these loads, achieving significant energy savings. Consequently, HVAC capital cost could be reduced considerably due to reduction of peak cooling loads.

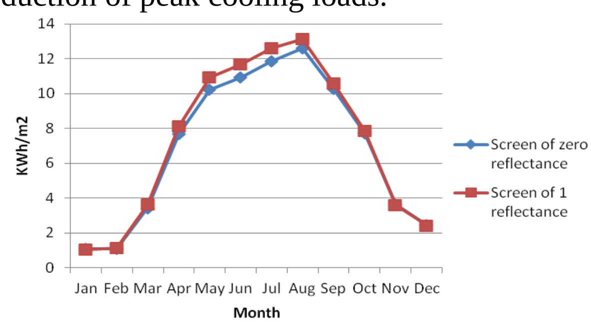


Figure 7: Monthly cooling energy for 80% perforated screens- South

## CONCLUSION

The results of this paper pave the way for the re-utilization of the traditional forms of solar screens in an informed energy efficient manner that achieves the performance goals of today's modern buildings. The paper demonstrated that proper selection of solar screen surface reflectivity can provide significant energy savings. Darker colored screens were more effective in comparison with light colored ones. Significant energy savings were achieved in the West and East orientations. The savings resulting from use of dark colored screens were more pronounced in screens having high depth and perforation rates. Increasing the depth of the dark colored screens blocked and absorbed the excess solar radiation, while increasing the perforation rate allowed for adequate daylighting which enhanced the total energy performance. Light colored solar screens with high reflectivity reduced lighting loads and heating energy. However, they caused a significant increase in the cooling energy, which resulted in a significant increase in the overall energy consumption in desert environment. These results confirm the wisdom of the traditionally developed screens which were typically built in dark colors with low reflectivity rates. However, these results cannot be generalized in all directions. Light colored screens showed some promising results in the South orientation. Screens with visible reflectance values up to 0.5 -especially those with screens of low perforation rates achieved the same -or better- energy performance in comparison with the traditional dark colored ones, when used with the recommended configurations. It general, light colored screens would be recommended in cases where diffuse daylight transmittance was needed, while and dark colored ones would be more suitable when maximum reduction in energy consumption was desired.

This research focused on orthogonal grid screens forms, having squared and rectangular fenestrations. More complicated screen configurations with different rotation and tilt angles could be investigated in further research. Experimental investigation should be conducted to confirm the simulation results, especially with different screen materials.

## ACKNOWLEDGEMENTS

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# HOURLY PLUG LOAD MEASUREMENTS AND PROFILES FOR A MEDIUM SIZED OFFICE BUILDING - A CASE STUDY

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## ABSTRACT

To determine the end use energy utilization profiles of major building subsystems – heating, ventilation, cooling, lighting, plug loads and/or servers – and accurately target potential energy efficiency improvement measures as well as establishing a building's performance relative to peer facilities, it is necessary to establish dynamic plug load energy use associated with occupant activity. As building façade, HVAC, and lighting component technologies improve and optimally employed in the context of the integrated design of a building, plug load related energy use becomes a more dominant component of the overall building energy utilization index. To clearly identify potential building subsystem energy efficiency improvements and develop strategies for ameliorating increases in plug load energy use via dynamic control and occupant awareness and involvement, rapid plug load measurement and assessment techniques are necessary. The current lack of measured plug load data that could be used as input for energy modelling has represented a significant gap in associating energy models with real building energy consumption. In this investigation, the circuits of multiple distribution panels were monitored to create hourly energy use plug load profiles associated with different end users within a tenant space of a medium-sized office building. The main use within the monitored space was associated with specialty conference rooms (ICON Lab and Telepresence Room), servers, workstations, copier/printer, kitchen amenities, and vacuum cleaning. Furthermore, the energy use data was further characterized according to day type (weekday and weekend). As a result of this work, hourly plug load profiles were generated based on actual measured data which will be used as input to energy models.

## KEYWORDS

Energy efficiency improvement, Hourly load profiles, Plug load, Measurements and verification, Weekday and weekend energy data

## INTRODUCTION

A product powered by means of an ordinary AC plug is defined as a plug load (Nordman & Sanchez, 2006). In the case of commercial buildings, plug loads are also referred to as Commercial Miscellaneous Electric Loads (C-MELs). That is all electric loads except those related to main systems including heating, cooling, ventilation, lighting, and water heating. To support its strategic planning efforts, DOE/BT contracted TIAX to characterize the state of C-MELs. In total, TIAX selected 28 key commercial MELs for further investigation (McKenney, et al., 2010). In their study, they considered nine building types including: office, retail & service (non-food), food service, food sales, education, warehouse, healthcare, lodging, and public assembly, order, and religion (AOR). Plug loads in residential and commercial buildings account for 12 percent of U.S. primary energy consumption (McKenney, et al., 2010). Energy use breakdown in commercial buildings indicate that plug loads account for up to 33% (Sheppy, et al., 2010).

Creating “as-operated” whole building energy models requires many inputs, including detail schedules for lighting and plug loads (Xu et al., 2013). Modelling tools employed throughout the industry are used both for projecting actual energy use as well as comparing energy use among alternative design options. The accuracy of these models greatly depends on variation in operational factors such as building schedule, occupancy, and plug loads. Once calibrated, an energy model is used in the performance analysis for energy conservation measures (ECMs) to find out which ECMs are the best option for the building (Pan et al., 2006).

As the implementation of Energy Conservation Measures (ECMs) for HVAC and Lighting systems become more common for high performance buildings, plug load has become a significant end user of electricity.

The objective of this study is to establish hourly load profiles for the end users within an office space and shed light on detailed information on usage patterns for various plug load equipment found in a typical office building, with the ultimate objective of establishing a coupled sub-metering and modelling effort that accurately accounts for plug load energy end use for internal load dominated buildings. Detailed energy use profiles have been developed relating to specific categories such as: specialty conference rooms (ICON Lab and Telepresence Room), servers, workstations, copier/printer, kitchen amenities, and vacuum cleaning, which were not available in the literature to the authors' knowledge.

## METHODOLOGY

The floor plan of the office suite under study along with the corresponding square footage associated with each area is provided in Figure 1. The true power of each plug load circuit utilized in multiple distribution panels was monitored using Veris multi-circuit power transducers (Version E31A). It should be noted that these measurements can be viewed instantaneously or as historically stored one-minute data.

A major effort in this study was dedicated to identifying circuits feeding the specific electrical receptacles within the space. This allowed for identification of very specific loads such as microwaves, toaster ovens, and refrigerators. This process can be a labor intensive, and therefore, costly component of energy auditing of a building with the aim to establish prioritized ECMs. Circuit finder tools were found to be unreliable in detecting the correct circuits associated with the electrical outlets. An IDEAL® circuit breaker finder tool was used as a starting point for detecting the circuits. The circuit was then verified by plugging in a Halogen Floodlight (utilizing a nominal 500-watt halogen bulb) and observing the step change in the related channel of Veris multi-circuit power transducer (detected by reading the instantaneous energy consumption data). It was necessary to cover some of the electrical outlets within the office space in order to ensure that one electrical circuit was not serving multiple end user categories (e.g. workstations and vacuum cleaner). In some cases the electrical outlet had to be blocked for use during the circuit identification, as these outlets were being powered by the circuits that were serving additional outlets outside the office space under investigation.

A preliminary equipment survey was performed in order to identify the "key" loads within the tenant space. Relatively inconsequential equipment such as electric pencil sharpeners was ignored. A summary of the key loads is provided in Table 1. It should be noted that detailed investigation of individual equipment power consumption is not the intent of this work.

| Space Type: | ICON Lab | Telepresence Room | Open Office | Porch Office | Lounge | Kitchen |
|---|---|---|---|---|---|---|
| Area ($ft^2$): | 1647 | 676 | 2374 | 1218 | 270 | 157 |

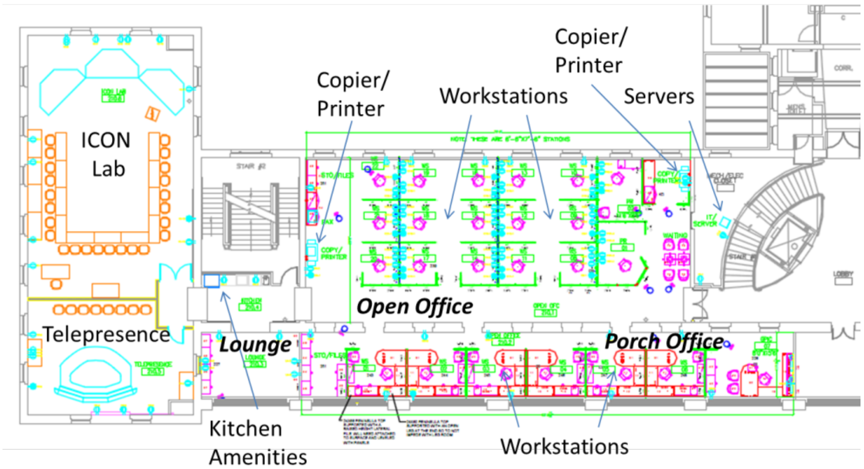


Figure 1. Office space floor plan and associated square footage.

Table 1. Equipment list for the office space.

| Product Type | Brand | Model | # |
|---|---|---|---|
| **Telepresence room** | | | |
| TelePresence Primary Codec | Cisco | CTS-CODEC-PRI-G2 | 1 |
| TelePresence Secondary Codec | Cisco | CTS-CODEC-SEC | 2 |
| TV (40 Inch LCD) | Cisco | CTS-DATA-DISP-40 | 1 |
| TV (65 Inch Plasma Display) | Cisco | CTS-DISP-65-GEN3 | 3 |
| **ICON Lab** | | | |
| Desktop | HP | Z800 | 1 |
| Desktop VNC | Dell | Precision T5500 | 1 |
| Desktop Smartboard | Dell | Optiplex 990 | 1 |
| Wireless Mic RX | REVOLABS | EXECUTIVE HD 8 | 1 |
| Audio DSP | BIAMP | NEXIA VC | 1 |
| Video Teleconference | TANDBERG | C60 | 1 |
| 5.1 AMP (Audio Amplifier) | DENON | AVR 2112CI | 1 |
| Controller | AMX | NI-3100 | 1 |
| SPYDER vedio processing | VISTA System | X20 1506 | 1 |
| AMP 1 (Power Amplifier) | QSC Audio | QSC ISA 300Ti | 2 |
| Desktop Monitor | NEC | LCD 2090UXi | 2 |
| Desktop Monitor | NEC | LCD 2490WUXi | 1 |
| Smart board (Projector) | Smart Technologies | UX 60 | 1 |

| | | | |
|---|---|---|---|
| LCD Monitors | Samsung | unknown | 1 |
| Main Projectors | Christie | Mirage WU7K-M | 3 |
| **Servers** | | | |
| Ethernet Switch | Alcatel | 6850-P24 | 1 |
| Wireless controller | Alcatel | 4504 | 1 |
| Server | Dell | R510 | 1 |
| Ethernet Switch | Cisco | 2800 | 1 |
| Network Interface | Canoga Perkins | 91475E-101 | 1 |
| UPS | Dell | UR1920W | 1 |
| Ethernet Switch | Cisco | Catalyst 3750 | 1 |
| **Office** | | | |
| Desktop | Dell | Precision T550 | 7 |
| Desktop | Dell | Optiplex 990 | 6 |
| Desktop | Apple | Mac Pro | 1 |
| Laptop | Dell | Latitude | 1 |
| Laptop | Apple | MacBook Pro | 1 |
| Laptop | Apple | MacBook Pro | 1 |
| Laptop | HP | HP Compaq 2510p | 1 |
| Monitor (Flat Panel 24") | Dell | U2410 | 14 |
| Monitor (Flat Panel 24") | Dell | ST24 | 1 |
| Monitor (Flat Panel 22") | Dell | P2211H | 16 |
| Monitor (Flat Panel 24") | Dell | G2410 | 2 |
| **Copier/printer** | | | |
| Multifunction Color | RICOH | Aficio MP C2551 | 1 |
| Printer | HP | HP LaserJet P4015x | 1 |
| **Kitchen Amenities** | | | |
| Refrigerator | KitchenAid | KBFS22EWMS3 | 1 |
| Microwave Oven | GE | JES1656SR1SS | 1 |
| Wide Base Coffee Brewer (SmartWAVE) | BUNN | WAVE 15-S-APS, WB LP PF | 1 |
| 2 Slice Toaster | Oster | TSSTTR6307 Toaster | 1 |

# RESULTS

Historical one-minute data was used as the input to a data analysis program developed in MATLAB. Hourly averages for the relevant circuits were computed and the data for the various circuits were summed to compute the overall end use energy based on the particular load category.

The main users within the space were identified as specialty conference rooms (ICON Lab and Telepresence Room), servers, workstations, copier/printer, kitchen amenities, and vacuum cleaner. Furthermore, the energy use data was grouped according to day type (weekday and weekend) in order to ascertain the difference between normally occupied and unoccupied times. The plug load profiles for the above mentioned end users are presented and disused in the following sections.

**Specialty conference rooms (ICON Lab and Telepresence Room)**
Specialty conference rooms were found to be the main consumers of electricity in the tenant space. The existence of the pieces of equipment that are required to constantly draw power generates a base load of 2 kW. It should be noted that ICON Lab equipment is contributing about 1.5 kW of the above mentioned 2 kW base, plug load. Figure 2 depicts the load profiles for weekday and weekend for the Telepresence room and ICON Lab.

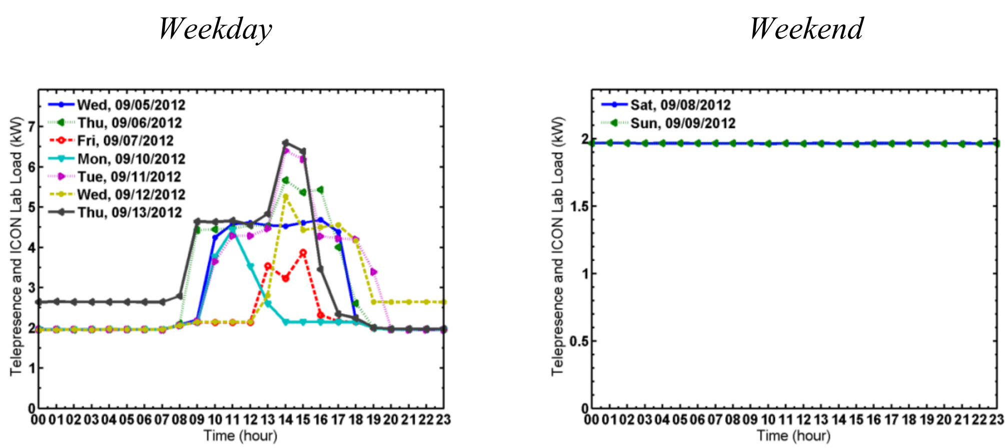


Figure 2. Plug load profile for Telepresence room and ICON lab.

**Servers**
Servers are also another contributor of plug load in the tenant space. As it can be observed from Figure 3, servers in the office under study are on all the time, with a resultant power consumption of approximately 0.65 kW.

**Workstations**
Workstations are also major consumers of electricity. Workstation loads include desktops, laptops, monitors, desk lamps, phone chargers, and any other electronic equipment that might be plugged in at a workstation. Plug Load profiles for the workstations for weekday and weekend are depicted in Figure 4. As it can be observed, some computers seem to be on all the time, which requires further investigation to make sure it is justified. It is intended that this data become part of an occupant awareness and involvement program. It should be noted that this office space is not typical for commercial office

space, i.e., the coincident factor of the workstations is smaller than what would normally be found in a commercial office settings.

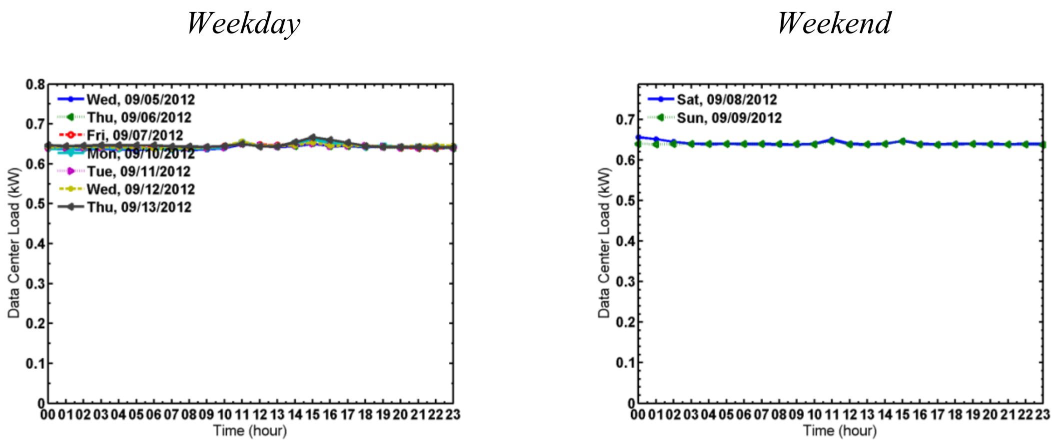


Figure 3. Plug load profile for servers.

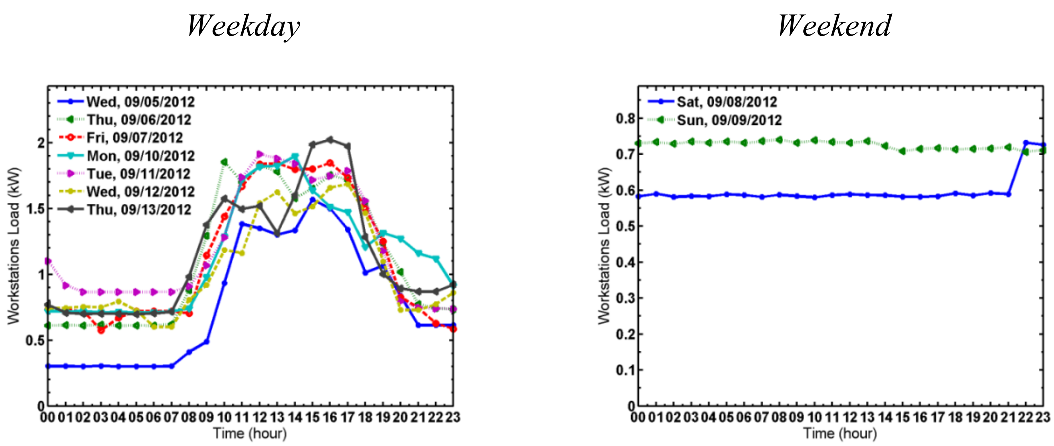


Figure 4. Plug load profiles for workstations.

**Copier/printer**

Copier and printer hourly profiles for the weekday and weekend are provided in Figure 5. As it can be observed from this figure, the copier and printer consumption was significantly higher on Tuesday, September 11, 2012 during the afternoon hours. This was due to the preparation of the hard copy material for a large meeting the following day.

**Kitchen amenities**

The weekday and weekend hourly load profiles are provided for the kitchen amenities including a refrigerator, a microwave oven, a toaster, and a coffee brewer (Figure 6). The data indicates that there is more usage for the kitchen during specific times in the morning and afternoon (which would be expected). Also, due the coffee preparation for the meeting on September 12, the usage was significantly higher.

*Weekday* *Weekend*

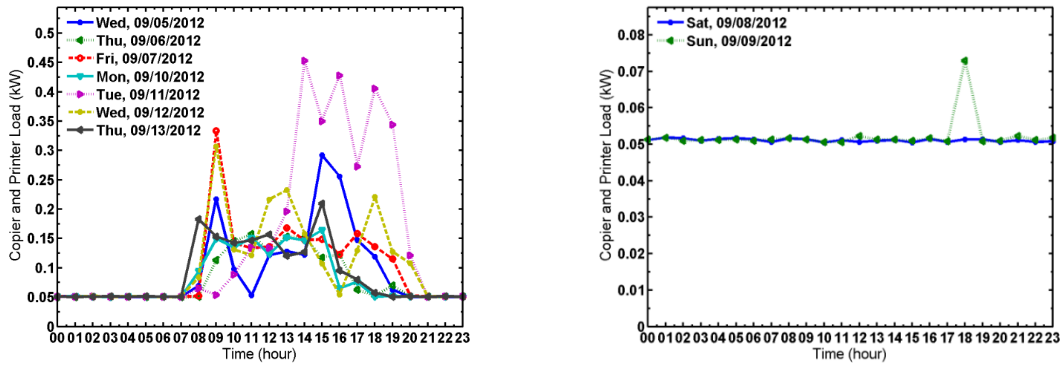


Figure 5. Plug load profiles for copier/printer.

*Weekday* *Weekend*

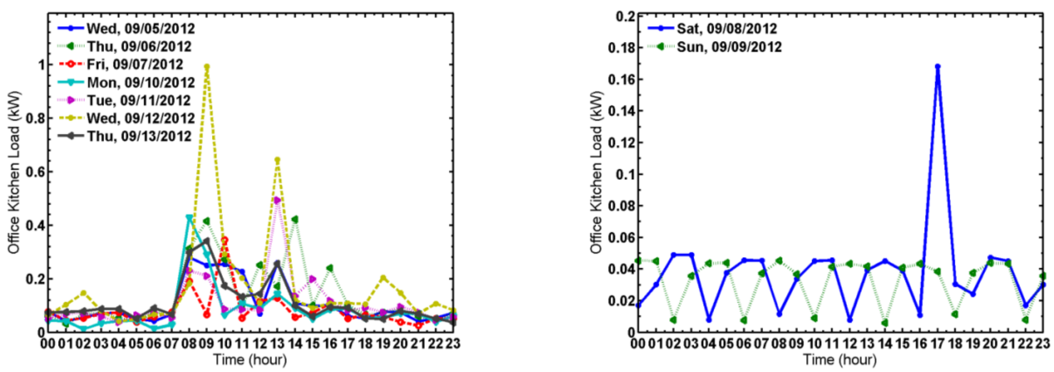


Figure 6. Plug load profile for kitchen amenities averaged over one hour interval.

*Weekday* *Weekend*

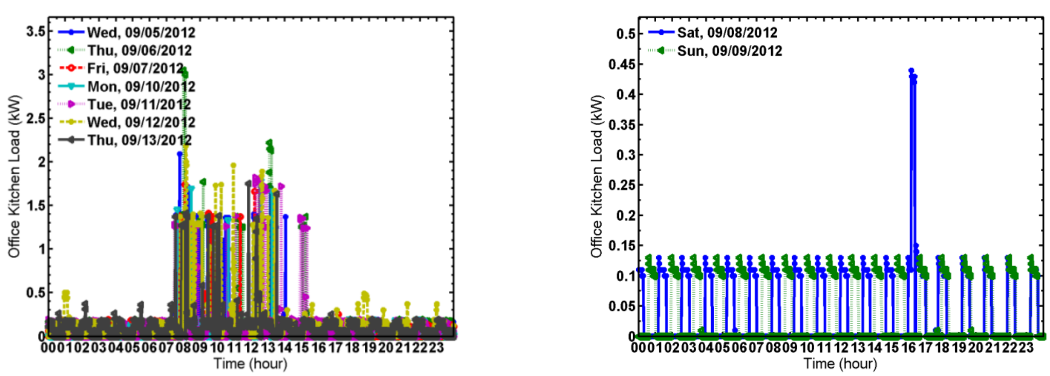


Figure 7. Plug load profile for kitchen amenities averaged over one minute interval.

The effect of calculating the average power over the period of one hour (averaging 60 numbers) can be better investigated by plotting the original one minute data (Figure 7). Figure 7 depicts the magnitudes of the power peaks for one minute intervals. (The significantly larger peak observed around 4 PM in Figure 7 probably occurred as the result of an automatic defrost cycle.)

**Vacuum cleaner**

The final category of the loads investigated in this study is the vacuum cleaner load. The vacuum cleaner load profiles for the weekday and weekend are depicted in Figure 8. It should be noted that the data (when there is no vacuuming occurring) indicates the existence of a bias error of approximately 0.01 kW.

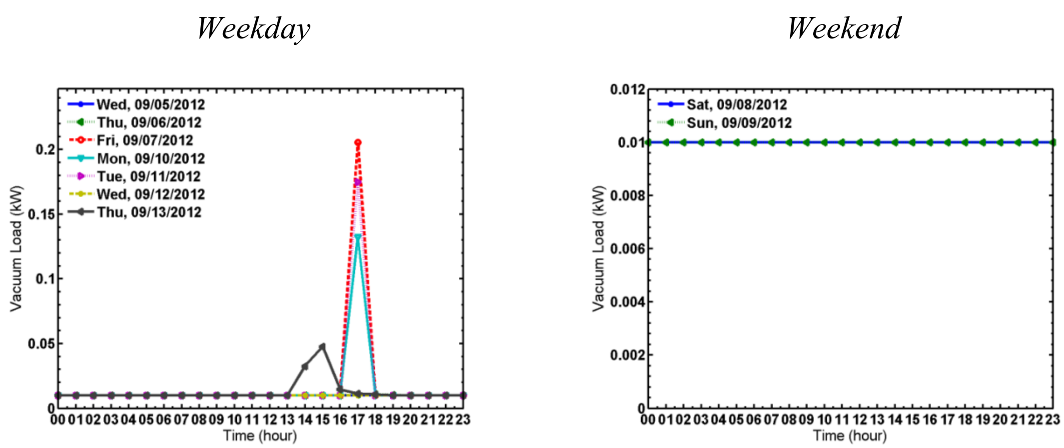


Figure 8. Plug load for vacuum cleaner.

## CONCULSIONS AND FUTURE STUDY

The plug load related energy use was investigated in this study. Hourly load profiles for the main users within the space were presented and discussed. Specialty conference rooms were found to be the major consumers of the electricity. The building schedules and behavioral aspects were found to be significant in the plug load profiles' shape and magnitude. A stratified random sample of the buildings along with protocoled-based, standard methodologies for determining plug loads are required to further investigate the problem. Predictive control of the building based on the occupancy schedules and event types is another topic that requires further investigation.

Characterizing plug load energy end use is necessary to establish quantitative "as operated" models of a building that allow prioritized ECM measures to be identified with low risk. Identifying the correct circuit distribution network for plug load determination can be time consuming if initial panel and sub-panel distribution design, or, as frequently occurs, modification due to changing building use is done without end use sub-metering in mind. However, as plug loads become a greater fraction of total building energy use they must be clearly isolated and quantified for rationale ECM planning. In addition, as occupant awareness and involvement becomes a major component in efficient building operation, occupants must have readily available data to determine their responsible use of energy while maintaining productivity.

## ACKNOWLEDGEMENT

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# REVIEW AND PRELIMINARY EVALUATION OF THE PERFORMANCE OF WEATHER RESISTIVE BARRIERS UNDER SEISMIC INDUCED LIGHT FRAME WALL DEFORMATIONS

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## ABSTRACT

Air, water, and vapor barriers, collectively referred to as weather resistive barriers (WRB), are an essential component of the modern building envelope system. If water passes through the WRB to the interior of the wall assembly, a moist environment is created around framing members and interior drywall, leading to decay and mold growth. Therefore, in order to protect against the adverse structural and health effects associated with moisture entrapment in the wall assembly, the WRB must be protected against tear and puncture, maintaining a proper air and waterproofing layer. One concern that has arisen amongst engineers is the capacity of the WRB to resist tearing when the light-frame wall assembly, including sheathing, is subjected to seismic induced racking displacements. The objective of this paper is to evaluate the serviceability and ultimate performance of the WRBs, and characterize the potential failure mechanisms based on available literature and test results.

**Keywords:** Liquid-applied membrane, Mechanically fastened membrane, Self-adhered membrane, Seismic loading, Weather resistive barrier

## INTRODUCTION

When one thinks of a building failure, the common thought is of partial or total building collapse. However, most building failures are related to serviceability issues and are due to water penetration through the building envelope. When water enters the wall system, rotting of wood stud walls, corrosion of steel beams or columns, and mold growth are just a few of the costly problems that may arise. Many common building types employ a cavity wall system in which the exterior walls consist of wood or steel stud framing, sheathing (oriented strand board, plywood, exterior gypsum board, etc.), insulation, an air gap, and a cladding (brick, stone, etc.). The weather resistive barrier (WRB) is the second line of defense against water penetration. Typically, the WRB is applied on the exterior side of the sheathing, and can be applied in one of the following manners: mechanically fastening membrane sheets, self-adhering membrane sheets, or a liquid-applied membrane created by spraying or rolling the material over the sheathing. In each case, the objective is to provide a continuous air seal and waterproof the wall. Regardless of the cladding type used, some amount of water is expected to enter into the wall cavity through joints, discontinuities, or damage to the façade.

Traditional materials used as WRBs were based on papers and felts, derived from cellulose and other organic fibers treated with asphalt (Butt 2005). In the 1980s, polymeric "house wraps" were introduced, and later, polymeric self-adhering sheets were marketed to provide better flashing around envelope penetrations (Butt 2005). Today, a variety of liquid applied membranes are available, which have varying chemical compositions of polymer modified asphalts.

A lack of knowledge and information exists about the performance characteristics of weather resistive barriers under building deformations or drift resulting from lateral loads (wind or earthquake). The breadth of information available is limited to products and marketing literature provided by the manufacturers. Testing results reported by the manufacturers range from water penetration and vapor and air permeance, to elongation, tensile strength, puncture strength, adhesion strength, etc. However, because of the use of different test methods by different testing labs, product comparison will be difficult.

With increasingly intricate architectural designs and complicated building envelope details, the evaluation of the performance of WRBs under the structural response of the building envelope is essential, especially in seismic and extreme weather conditions. Seismic design and detailing of a building is determined by building code prescribed approaches, where some damage to buildings is expected, and life safety is the main concern. WRBs (and their associated flashing components), once installed, are not typically accessible for maintenance and repair, but are expected to remain serviceable for the service life of the building wall assembly. If during a seismic event the WRB tears, mechanical fasteners pullout, or the membrane releases from the substrate, the result is a breached building envelope that will most likely go unnoticed until potentially extensive damage has been done. The financial implications of this damage may be significant.

## LITERATURE REVIEW ON WRB TYPES

### Polymer Technology

Self-adhered and liquid-applied membranes are elastomeric membranes with a wide range of compositions. An elastomer or elastomeric membrane refers to a material that is rubber-like in nature with typical material properties such as 500-1000% elongation, instantaneous recovery, an initial modulus of 15-150 psi, and high tensile strength (Orchon 1985). Many membrane products have a polymer modified asphalt material composition. Additionally, the self-adhered sheets incorporate a cross laminated thermoplastic film. The chemical composition of asphalts is extremely complex and variable, so the chemical composition of asphalt cannot be exactly defined, and the internal structure in almost unknown (Polacco et al. 2006). Polymer modified asphalts are mixed in a way such that the polymer characteristics will tend to determine the behavior of the blend, offsetting the lack of knowledge associated with the asphalt structure (Polacco et al. 2006).

The main categories of polymer modifiers are thermoplastic elastomers, plastomers, and reactive polymers. Thermoplastic elastomers enhance elastic recovery capacities and resistance to permanent deformations, but can be expensive and exhibit problems with degradation (Polacco et al. 2006). Plastomers, such as polyethylene and polypropylene, can reduce these problems and are commonly listed in the material composition in the manufacturer supplied membrane literature.

**Product Review**

This section highlights popular mechanically-fastened, self-adhered, and liquid applied membranes available in the current building construction market. Manufacturers of these products include, but are not limited to; Dupont, Carlisle, Grace, Henry, Momentive, PROSOCO, Tremco, and W.R. Meadows. Products made by some of these manufacturers will be reviewed.

***Mechanically Fastened Barriers***

One of the most prevalent mechanically applied air and weather resistive barrier is DuPont Tyvek (Figure 1). Tyvek is a spunbonded olefin sheet product made from high density polyethylene fibers. Spunbonded olefin is formed by a continuous process from very fine .5-10 µm fibers. The nondirectional fibers (plexifilaments) are first spun and then bonded together by heat and pressure without a binder. The resulting material is strong, lightweight, flexible, smooth, resistant to water, chemicals, abrasion, and aging. Two different structure types of spunbonded olefin are available. Type 10 is a "hard" area bonded product that has a smooth, stiff nondirectional paper-like substrate. Types 14 and 16 are "soft" providing a fabric like flexible substrate.


Figure 1: Mechanically Fastened Barrier applied to a Building Exterior

A number of different fasteners can be used to attach Tyvek: DuPont 2" plastic cap screws (for steel or wood frame construction), 1 ¼" metal gasketed washers with screws (for steel frame construction), 2" metal gasketed washers with screws (for steel frame construction), 1" plastic cap staple with leg length sufficient to achieve 5/8" penetration into wood stud (for wood frame construction), #4 nails with 1" plastic cap (for wood frame construction), and Tapcon fasteners with 2" plastic cap (for masonry construction).

***Self-Adhered Membranes***

Self-adhered membranes are rolled sheets that are attached to the building substrate by means of an adhesive on the back of the membrane (peel-and-stick application). Self-adhered membranes have advantages over mechanically fastened membranes in that they are fully adhered to the substrate, so no punctures or tears from nails or staples are present. The rolled sheets create a membrane of uniform thickness that is both flexible and self sealing. Self-adhered membranes are comprised of a rubberized asphalt compound that is integrally laminated to a cross laminated high density polyethylene film. Typical membrane and film thicknesses are .9 mm and .1 mm respectively. The film is located on the exposed face of the membrane and is intended to provide dimensional stability, and strength against tearing, puncture, and impact.

Table 1: Self-Adhering Air and/or Vapor Barriers

| No. | Manufacturer Product | Tensile Strength[1] (psi) | Elongation[1] | Peel Strength[2] (lb/in width) | Puncture Resistance[3] (lbs) | Lap Adhesion[4] (lb/in width) |
|---|---|---|---|---|---|---|
| 1 | Carlisle CCW-705 | 500 | 300% | 7.5 | 50 (min) | 7 |
| 2 | Grace Perm-A-Barrier | 400 (membrane)<br>5000 (film) | 200% | - | 40 | 4 |
| 3 | Henry BlueskinVP 160 | 41 lb[6] | Pass[7] | Pass[8] | - | - |
| 4 | Poly Wall Self-Adhering Sheet Membrane | 325 (membrane)<br>6500 (film) | 600% | 15[5] | 40 | 8[5] |
| 5 | Tremco ExoAir 110/110LT | 500 (membrane)<br>5000 (film) | 250% | - | 55 | - |
| 6 | W.R. Meadows Air-Shield | 4000 (film) | 400% (film) | 10 | 40 | - |
| | ***Average Values*** | *425 (membrane)*<br>*5100 (film)* | *350%* | *10* | *45* | *6* |

1. ASTM D412 - Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers-Tension
2. ASTM D903 - Standard Test Method for Peel or Stripping of Adhesive Bonds
3. ASTM E154 - Standard Test Methods for Water Vapor Retards Used in Contact with Earth Under Concrete Slabs, on Walls, or as Ground Cover
4. ASTM D1876 - Standard Test Method for Peel Resistance of Adhesives (T-Peel Test)
5. ASTM D1000 - Standard Test Method for Pressure-Sensitive Adhesive-Coated Tapes Used for Electrical and Electronic Applications
6. ASTM D882 - Standard Test Method for Tensile Properties of Thin Plastic Sheeting
7. ICC-ES AC48 - 100 cycles at -20ºF
8. ICC AC38/AAMA 711-05

Table 1 shows material information and test data for self-adhering air and/or vapor barrier products by leading manufacturers. Tensile strength and elongation values are critical properties for determining the performance of the membrane under building drifts. The percent of elongation corresponds to the maximum tensile strength, which is the load required to tear the membrane. Therefore, if the elongation of the membrane is exceeded, tearing will occur. Average values can provide an overall representation of the performance of self-adhering membranes. The averages are obtained by taking the sum of the product values divided by the number of products summed. The average tensile strength is 425 psi (products 1, 2, 4, 5) for the membrane (5100 psi for the film, however, the membrane is the limiting value), a 350% elongation (products 1, 2, 4, 5 6), 10 lb/in. width peel strength (products 1, 4, 6), 45 lb puncture resistance (products 1, 2, 4, 5, 6), and 6 lb/in. width lap adhesion strength (products 1, 2, 4). It should be noted that the lap adhesion value is slightly less than peel strength, so failure should occur at the seams before the product unadheres from the substrate.

Blueskin VP 160, produced by Henry Company, is an example of a vapor permeable, self-adhered water resistive and air barrier membrane. Blueskin VP 160 is comprised of an engineered film backed with a permeable adhesive technology and split-back poly-release film. The engineered film is a tri-laminate polypropylene fabric and the adhesive is a synthetic polymer blend with thermal-plastic properties. The adhesive used in this product is a pressure sensitive adhesive (PSA). Initially, the PSA will only stick to the high points along the rough substrate surface, but once pressure is applied and time lapses, the adhesive will flow and increase surface area contact, thus increasing the adhesion.

***Liquid Applied Membranes***

Unlike mechanically fastened sheets and self-adhering membranes, liquid applied membranes cure to form a continuous flexible elastomeric membrane without laps or seams, which can accommodate typical designed building movements. Table 2 shows material information and test data for liquid applied air and/or vapor barrier products produced by leading manufacturers. Similarly to self-adhered membranes, tensile strength and elongation are critical properties because they indicate when tearing of the membrane will occur. Representative averages can also be obtained from the provided data using the same methodology used for the self-adhered membranes. The average tensile strength is 164 psi (products 1, 2, 4, 5), a 547% elongation (products 1-7, the 1500% value associated with product 8 was not included in order to maintain a more accurate representation), a 10.5 lb/in. peel strength (products 2, 7, 8), and 51 psi adhesion strength (products 2, 3, 5, 6, 7. This value is not very representative based on the substrate used in testing).

SEC2500 SilShield AWB is a liquid silicone air and water barrier by General Electric Company under license by Momentive Performance Materials Inc. (Figure 2). SEC2500 is a single-component liquid that can be applied to many typical substrates by spray, roller, or brush without the need for a primer. This is a 100% silicone coating that address adhesion and compatibility challenges that may arise during construction. SEC2500 is compatible and will bond with silicone materials used to seal and glaze windows, doors, joints and other façade features. Prior to the application of liquid-applied membranes, cracks and joints between sheathing panels should be filled with a troweled on layer of the polymer material and then reinforced with compatible transition strips.

Table 2: Liquid Applied Air and/or Vapor Barriers

| No. | Manufacturer Product | Material Composition | Tensile Strength[1] (psi) | Elongation[1] | Peel Strength[2] (lb/in) | Adhesion Strength[3] (psi) |
|---|---|---|---|---|---|---|
| 1 | Carlisle Barritech VP | Single-component membrane | 175 | 500% | exceeds facer strength | - |
| 2 | Dupont Tyvek Fluid Applied WB | Single-component elastomeric polyether-based polymer product | 169 | 420% | 13.3 | >25* |
| 3 | Grace Perm-A-Barrier Liquid | Two-component synthetic rubber, cold-vulcanized membrane | - | 500% | - | 18* |
| 4 | Henry Air-Bloc 31MR | Single-component, water-based, rubber-like membrane | 138 | 925% | - | - |
| 5 | Momentive SEC2500 SilShield | 100% Silicon | 175 | 350% | - | 33 |
| 6 | Poly Wall Airlok Flex VP | Single-component, water-based, polymeric membrane | - | 500% | - | 100+ |
| 7 | TK AirMax 2102 NP | Single-component rubberized polymer formulation | - | 637% | 11.9 | 81.6 |
| 8 | Tremco ExoAir 120 | Polymer-modified emulsion | - | 1500% | 6.5 | - |
| | ***Average Values*** | - | *164* | *547%* | *10.5* | *51* |

*delaminates fiberglass topsheet
1. ASTM D412 - Standard Test Methods for Vulcanized Rubber and Thermoplastic Elastomers-Tension
2. ASTM D903 - Standard Test Method for Peel or Stripping of Adhesive Bonds
3. ASTM D4541 - Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers

Figure 2: Finished application of SEC2500 SilShield to Mock-up Wall
Source: Momentive Performance Materials

# REVIEW OF TEST STUDIES

### Testing of Weather Resistive Barriers

Testing of waterproofing membranes in response to wind uplift and suction pressures for application in roofing systems has been studied extensively. Mechanically-fastened membranes subjected to wind load tend to balloon as a result of pressure differentials acting across the membrane surface. The ballooning and corresponding deflection of mechanically-fastened membranes has been studied by Baskaran et al. (2009), Shi et al. (2006), and Shi and Burnett (2008).

Miyauchi et al. (2010) and Miyauchi et al. (2011) have extensively studied the fastener sections of mechanically-fastened membranes. Much attention has been paid to the fasteners because frequently problems such as fastener damage, fastener pullout, and membrane fracturing occur at the fastener location, as they resist the uplift forces. The studies show that the load applied to the fasteners is directly related to the tributary area of each fastener, and that the only way to reduce the loading is to decrease the fastener spacing. The studies examine the effects of both axial and lateral forces acting on the fasteners. In the wind tunnel test conducted by Miyauchi et al. (2010), a wind speed of 86 mph (38.6 m/s) produced an axial force of 34 lb (151 N) and lateral force of 23.4 lb (104 N) at the fastener locations. The results show that a significant lateral force occurs at the fasteners, which is thought to be the cause for tearing of the waterproofing membrane in the lateral direction in high wind events.

Testing on weather resistive barriers has primarily been focused on the performance characteristics of water resistance and vapor permeance. Such testing has been carried out by Bomberg et al. (2005), Butt (2005), Kumaran et al. (2006), and Weston et al. (2006). Water resistance is commonly measured using two test methods: AATCC Test Method 127 (hydrostatic pressure test) or a variation of ASTM D779 – Water Resistance of Paper, Paperboard, and Other Sheet Materials by the Dry Indicator Method (boat test). AATCC35 – Test Method for Water Resistance: Rain Test is a smaller scale test that may also be used to measure water resistance. The standard test for determining vapor permeance is ASTM E96 – Standard Test Methods for Water Vapor Transmission of Materials.

### Testing of Light Frame Shear Walls

Extensive research has been performed on light frame shear walls with the objective of providing a better understanding of the response of shear walls under loading conditions that more accurately represent a seismic loading scenario. Both analytical and experimental testing has been performed on light frame walls, and attention has been focused on various effects of panel size and type, fastener type, and the effect of hold-downs (Folz and Filiatrault (2001) Li and Ellingwood (2007)). The response of light frame shear walls to cyclic loading is relevant because it characterizes the wall behavior that the WRB will need to endure, as the WRB will not provide added seismic resistance for the wall assembly. Typically, wood shear walls will experience lateral drifts of 2 – 4% under the ultimate load-carrying capacity of the wall.

The failure mechanism of certain types of light frame walls under seismic induced loading has been characterized in tests conducted by Gatto and Uang (2003), Timber Products Inspections Inc. (1990), Intertek Testing Services (2003), and Terentiuk and Memari (2009). The first signs of failure are associated with the nails. These failures include nail pullout and pullthrough, tearout, and fracture. Nailing failures typically occur at the panel edges. Testing by Terentiuk and Memari (2009) reported nail pullout up to 2 in. when 2 ½ in. nails were used. Other failure mechanisms observed include separation of the panels in both the vertical and horizontal plane, separation of the sheathing from the top plate, damage to the studs (particularly end studs), and damage to the holdowns. Terentiuk and Memari (2009) recorded values for panel separation on both structural insulated panels (SIPs) and woodframed shear walls. Maximum horizontal and vertical displacement recorded on the SIP walls were 2 ½ in. and 1.3 in. respectively. Maximum horizontal and vertical displacements recorded for the woodframed shear wall were .4 in. in each direction.

## DISCUSSION

### Probable Failure Mechanisms

Mechanically fastened WRBs would most likely perform the worst after a high seismic event. While the barrier material is sufficiently strong, performance is based on the fasteners and tearing around the fastener locations. Failure of the nails is significant in light frame construction. If nail pullout up to 2 in. is observed, than nails used in fastening the membrane to the sheathing will most likely pullout as well, thus, leading to a failure of the membrane.

Nail pullout and panel rotation/separation are the two failure mechanisms with the greatest effect on both the self-adhered and liquid-applied membranes. Nail pullout corresponds to the puncture strength of the membrane. The withdrawal strength required for a 2 ½” in. 16d nail in ½ in. sheathing and Hem. Fir No. 2 studs is 86 lbs. (American Wood Council 2006). This is greater than the average puncture strength of self-adhered membranes (45 lbs.), so puncture and tearing of the membrane is likely. However, while the 86 lb. withdrawal load considers the time duration factor for seismic loading, the effects of nail hole deformation are not considered. If the nail hole was to deform significantly under racking loads, the required withdrawal value could decrease significantly. For this reason, puncturing of the membrane cannot be accurately determined without further testing.

Panel rotation correlates to the elongation of self-adhered and liquid-applied membranes. If it is assumed that the panels initially have a 1/16 in. gap at the time of construction and have a .4 in. gap after racking tests, then the membrane would have to elongate 640%. A 640% elongation is greater than the average value for self-adhered membranes (350%) and liquid-applied membranes (547%). Maintaining an initial gap of 1/16 in. and the average elongation values, the maximum allowable panel separation for the self-adhered membrane would be .22 in. and the maximum allowable panel separation along vertical sheathing joints for the liquid-applied membrane would be .34 in. Looking at the products individually, none of the self-adhered membranes provide sufficient elongation for a .44 in. separation, however, two of the liquid-applied membranes have reported elongation values of 925% and 1500%, which seems to be adequate.

**Future Testing**
A testing program should be performed on WRBs from each category of products. The testing program would include a series of four tests. The assembled wall specimen would be tested in accordance with ASTM E283-04 to determine the rate of air leakage through the wall assembly, and to set a baseline. Then ASTM E564-06 would be followed for the static load (monotonic) test and ASTM E2126-11 would be followed for in the in-plane racking (cyclic) testing of the wall assembly. The wall panel would be tested for air leakage again to determine effect of lateral loading on the performance of the weather resistive barrier. Failure mechanisms for each of the membranes can be observed and the results of testing can be correlated to manufacturer provided data.

## SUMMARY AND CONCLUSIONS

Weather resistive barriers are an important part of the building envelope responsible for controlling air, vapor, and water transmission through the wall assembly. WRBs need to be able to resist lateral loads (seismic and wind) applied to building to properly function through their service life. Based on available testing information, the following can be concluded:

- Tensile strength, elongation, and puncture resistance are the critical properties for estimating membrane performance under seismic induced light frame building deformations.
- Average tensile strength, elongation, and puncture strength for self-adhered membranes is 425 psi, 350%, and 45 lbs respectively.
- Average tensile strength and elongation for liquid-applied membranes is 164 psi and 547% respectively.
- Mechanically fastened membranes will likely fail at the fastener locations as a result of fastener pullout and/or tearing around the nail holes.
- Nail pullout, observed in woodframe shear wall racking tests, may lead to puncturing of self-adhered and liquid-applied membranes.
- Average values for elongation of self-adhered and liquid-applied membranes appear to be inadequate to accommodate panel rotation observed in light frame racking tests. However, a couple of liquid-applied WRBs appear to have sufficient elongation to accommodate an average panel separation of .44 in.
- Laboratory testing is required to correlate estimated and actual performance of WRBs under seismic induced light frame building deformations.

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# REDUCING IMPACT OF WIND ON TALL BUILDINGS THROUGH DESIGN AND AERODYNAMIC MODIFICATIONS

**(Architectural and Structural Concepts to Mitigate Wind Effect on Tall buildings)**

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**ABSTRACT**

The structure of tall buildings, in addition to gravity loads, is to resist lateral loads, resulting from wind, earthquake, etc. Wind produces three different types of effects on tall buildings: static, dynamic, and aerodynamic. Structurally, static effect is a term of analysis independent of time; but dynamic analysis is an attempt to take into account how the system responds to the change through the period of time; and when the building is very flexible, it interacts with the wind load and affects its response; that is called aerodynamic effect. The dynamic response of tall buildings to lateral load, particularly wind, is affected by several factors including structural stiffness, mass, damping and architectural shape and form. To control the dynamic impact, there are two main solutions: Architectural and Structural. Architects can mitigate wind effect on tall buildings by designing the form aerodynamically or at least by utilizing aerodynamic modifications, which are categorized in macro and micro modifications. Structural engineers can also reduce wind effect by choosing and designing efficient structural systems. This paper presents an overview of the impact of wind on tall buildings, along with some structural and architectural strategies to mitigate wind effects.

**Key words:** Aerodynamic modification, Dynamic response, Tall building, Vortex shedding, Wind.

## THE EFFECT OF WIND ON TALL BUILDINGS

From one side, tall building acts like a free standing cantilever beam, since it becomes more susceptible to lateral loads the taller it is. From the other side, wind as the term used for air in motion or the natural horizontal motion of the atmosphere is considered as one of the main lateral loads in facing with tall buildings. Structurally, regarding the relationship between height and the wind velocity and also the pressure (Figure1), wind as one of the main lateral loads acts like a foe in facing with tall buildings; although, in some cases like natural ventilation and energy, acts as a friend for buildings. Note that the curves shown in (Figure1) can approximately be extended to height over 1500 (ft). As the wind speed increases, the wind pressure on the building increases proportionally with the square of the wind velocity (P α V²) and varies dynamically relative to the degree of shielding provided by other buildings and geographic features. [Taranath, 2005]

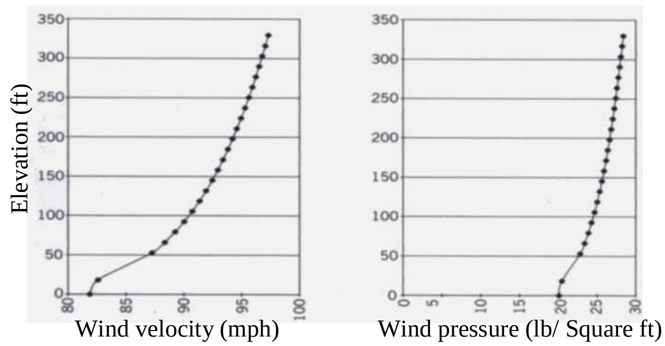


Figure 1: The relationship between height, velocity and pressure (Sarkisian, 2012)

The behavior of wind in reference to slender structure is complex. One of the reasons of the complexity is that, tall buildings are subjected to wind induced along as well as across wind direction. Structurally, when considering the response of a tall building to wind, both along wind and across wind responses must be considered. In this path, although the maximum lateral wind loading and deflection are usually observed in the along wind direction, the maximum acceleration of a building loading may occur in across wind direction. [Taranath, 1998] Also, when the frequency of wind becomes approximately close or the same as the natural frequency of the building, the across wind effect causes vortex shedding, that is so a critical parameter in the structure of tall buildings.

## STRUCTURAL AND ARCHITECTURAL STRATEGIES TO MITIGATE WIND EFFECT

To reduce the impact of wind on a tall building and mitigate the response of the structure of tall building, there are two main concepts: Architectural and structural. Architects by considering the effect of form and geometry and structural engineers by considering the structural systems can mitigate the static effect as well as dynamic effect of wind on tall buildings. In this paper, besides a brief explanation of structural strategies, the architectural one will be illustrated to evaluate and to achieve the mitigation of the response of a tall building.

### 1. Structural strategies

There are two main structural concepts to reduce the response of tall buildings to wind:

### 1.1.Increasing the structural stiffness by considering the structural systems

The first solution comes to the mind is to control the wind response by stiffening the structure. For taller buildings, particularly slender ones, it may be extremely expensive to provide enough stiffness as a solution to control dynamic response; thus, in general this concept is not efficient and often appropriate for shorter buildings unless, stiffen the structure by accomplishing the structural systems such as all kind of tube systems, outrigger and diagrid systems.

Based on the paper of [Ali and Moon, 2007], the structural systems of tall buildings can be divided into two main categories: interior structures and exterior structures. This concept of division is based on the distribution of the components of the primary lateral load resisting over the building and the location of that; in the interior or the perimeter of the building. For instance, moment resisting frame and outrigger structure with shear wall are considered as the interior systems and tube, diagrid and super frame systems are the examples of exterior structural systems.

One of the good examples to show the effect of the structural systems on the efficient parameters is the John Hancock tower with 100 stories in Chicago designed by Skidmore, Owings and Merrill with braced tube structural system; the steel weigh of this building is at a mere 29.7 lb/sq.ft (although it uses a total of 46,000 tons of steel that is maybe appropriate for around 50 stories building).

### 1.2.Damping sources

The second structural solution to reduce the response of tall buildings is damping. Damping is the degree of energy dissipation that a structure can provide to reduce build-up of the resonant response. It comes from two main sources: intrinsic and supplementary. Intrinsic means within the structural material, i.e., steel, reinforced concrete, and soil. Unlike intrinsic sources, supplementary or auxiliary damping, which is primarily mechanical or heat release dependent, have to be added to the slender tall buildings. Although not marked for high rise buildings, damping contributions may also be obtained from the soil foundation interaction, as mentioned.

In summary, damping devices are divided into two main groups: Passive systems and active systems. Passive systems can be categorized in two subdivisions:

- Energy- dissipating material based damping system, such as viscous dampers and visco elastic dampers, and
- Auxiliary mass systems like tuned mass dampers (TMD) and tuned liquid dampers (TLD).

Unlike passive systems, active systems can perform effectively over a much wider range of vibration, such as mass dampers (AMD) and active variable devices (AVSD).

## 2. Architectural strategies

In addition to the structural concepts to reduce the response of tall buildings against wind, the architectural strategies can act as the passive and precautionary methods to mitigate wind effect on the form of tall buildings. In this paper, as the architectural strategies are the main parts, different types of aerodynamic modifications and practical examples of these concepts will be explained.

### 2.1.Aerodynamic Forms

One of the recent trends in design of tall building is to improve the aerodynamic properties of the building to mitigate wind effect. This can be achieved by various treatments of buildings' masses and forms. Aerodynamic forms act like an unexpected form in a relationship with wind and can reduce the along wind response as well as across wind effect by confusing the wind. To have a more illustration about unexpected form, it is essential to explain that irregular aerodynamic forms can disperse the effect of wind to become an integrated huge power on the structure of tall building.

The Guangzhou Pearl River tower (Figure2) completed in 2011 in China with its funnel form facades and rounded edges that catch natural wind not only to reduce the building response but also to generate the energy of wind. Another interesting aerodynamic form of tall building is the Al Hamra Tower (Figure3). That is a topped out tall building in Kuwait City, Kuwait, completed in 2011 with 1,354 ft (412.6 m) tall. The curvilinear form of the building also prepares optimum views for the occupants.

Figure 2: Guangzhou Pearl River tower, China, (http://architectureyp.blogspot.com). Figure 3: Al Hamra Tower, Kuwait, (http://en.wikipedia.org)

### 2.2.Aerodynamic (Geometric) modifications

Tall buildings go higher and higher with advances in structural and architectural concepts on one side and high strength materials and technology from the other side. One of the important and effective design approaches among passive methods to control and mitigate dynamic response of tall buildings is aerodynamic modification in architecture.

Modifications on cross-sectional shapes, such as slotted, chamfered, rounded corners, and notching on a rectangular building, can have significant effects on both along wind and across wind responses of the building, as in Taipei 101. "Corner modifications provide 25% reduction in base moment when compared to the original square section." [Irwin, 2006] Hence, in many of the most famous buildings, these aerodynamically favorable forms are preferred. However, some studies have also shown that some modifications are ineffective and even have adverse effects; thus, there is no distinct consensus on the benefits of all aerodynamic modifications concepts in all the situations.

Aerodynamic modifications can be divided into two main groups:

- Macro modifications: Modifications that have effect on the main architectural concept, such as tapering, setting back and twisting.
- Micro modifications: Modifications such as all corner modifications having no effect on the main architectural geometry and form. [Ilgin&Gunel, 2007]

### 2.2.1. Tapering

It means to become gradually slender toward the top of the tall building. Tapering effect has a more significant impact on across wind direction than that in the along direction and "it is much more effective for suppressing the large size of vortex-shedding than the small size." [Amin. J. A &Ahuja A. K, 2010] However, investigations show increasing the tapering ratio could have an adverse effect when the structural damping ratio is very low.

In the paper of [Kim. Y and You. K and Ko. N, 2008], four types of building models which have different taper ratios of 5%, 10%, 15% and one basic building model of a square cross-section, with 80(mm) by 80(mm) plan with 320(mm) height, were tested under the two typical boundary layers representing suburban and urban flow environments. The author concluded that, tapering effects when the range of reduced velocity is high and the structural damping ratio is about 2–4% and when the damping ratio is below 1%, the increased taper ratio could adversely affect the responses causing motion-induced excitations to begin and at the high range of reduced velocities, the effect of increasing the taper ratio and increasing the structural damping ratio to reduce wind effect.

Figure 4: .John Hancock, Chicago, (Individual Album). Figure 5: F04.Chase Tower, Chicago, (Individual Album). Figure 6: Bahrain World Trade Center, Manama, (http://beforeitsnews.com).

In general, changing the cross-sectional shape of tall building like tapering along the vertical axis can be especially effective in reducing the crosswind forces. The John Hancock tower (Figure4) and Chase Tower (Figure5) both in Chicago and Bahrain World Trade Center (Figure6) are three examples of "tapering concept.

### 2.2.2. Setback

This is a kind of tapering and sculpting the tall building. In practice, "the more sculptured a building's top, the better it can minimize the along wind and across wind responses." [Kareem, Kijewski& Tamura, 1999] Setback not only sculptures the building, but also serves aerodynamic purposes to reduce wind effect, particularly across effect. "If the width of tall building can be varied up the height of the building, through tapering or setbacks, then the vortices will try to shed at different frequencies at different heights. Then, they become "confused" and incoherent, which can dramatically reduce the associated fluctuating forces." [Irwin, P. 2009] In the paper of [Kim and Kanda, 2010], the mean drag force coefficient at wind direction is reduced about 11% for the setback model, 7.7% for the 10% tapered model, and 3.8% for the 5% tapered model, when compared with the square section model (80(mm) by 80(mm) by 400(mm) height). The Jin Mao tower (Figure7) in Shanghai and the Petronas Towers (Figure8) in Kuala Lumpur, are two examples to slightly taper the building by this concept. Tapering and setback are the architectural-functional desire to reduce the volume of the building as it goes up in height.

### 2.2.3. Porosity or openings

Another very intellectual concept to improve the dynamic response of the structure to wind, by reducing the effect of vortices, is to add openings through the building at the certain locations of the building, particularly near the top. By considering this concept "the formation of the vortices becomes weakened and disrupted by the flow of air through the structure." [Irwin, 2009] This disruption causes to avoid vortices and allow the air to blow into the separated paths and consequently reduce the total aerodynamic forces.




Figure 7: Jin Mao tower, Shanghai, (http://www.china-tour.cn).Figure 8: Petronas Tower, Kuala Lumpur, (http://www.thepetronastowers.com). Figure 9: Kingdom Center, Riyadh, Saudi Arabia, (http://en.wikipedia.org). Figure 10: O-14 tower, Dubai, (http://desmena.com).

Shanghai financial tower and Kingdom Center in Saudi Arabia (Figure9) are good examples of this attitude. Another very interesting example is O-14 tower in Dubai (Figure10) built with concrete by considering this concept.

#### 2.2.4. Twisting

Although this concept arise some problems for the structural parameters, twisting is an effective strategy in reducing vortex shedding caused by the dynamic response of tall buildings. Twisting the building can be very effective to reduce wind effect, particularly for cross effect because its least favorable aspect does not coincide with the strongest wind direction and the wind is confused. This attractive form can be found in today's tall building designs, such as the 190 (m) high Turning Torso in Malmo, Sweden (Figure11) and the proposed Chicago Spire super tall building (Figure12), designed by Santiago Calatrava. In the latter one without twisting the structural elements, architect just by twisting the façade can achieve this architectural sight.

#### 2.2.5. Slotted and chamfered corner

Slotted and chamfered corners have considerable results in reducing the dynamic response in both along wind and crosswind directions in comparison of plain rectangular tall buildings. Although in the research of [Holmes, 2001] chamfers in the order of 10% of the building width, makes 40% reduction in the along wind response, and 30% reduction in the across wind response when compared to the rectangular cross sectional shape without corner cuts. Studies have also shown that corner modifications, in some cases, were ineffective and even had adverse effects depends on the diverse wind speed and direction and also the natural frequency of the buildings. New World Trade Center New York (Figure13) is one of the tall buildings utilizing by this concept.

#### 2.2.6. Corner roundness and recession

Rectangular shapes are very common for buildings and experience relatively strong vortex shedding forces. However, it is found that if the corners can be softened through chamfering, rounding or stepping those inwards, the excitation forces can be substantially reduced. In the paper of [Kwai. H, 1998] investigated that among corner cut, recession and roundness, the corner roundness is the most effective to suppress the aeroelastic instability for a square prism. The amplitude of the wind induced vibration reduces as the extent of the corner roundness increases. Wuhan Greenland Center, China (Figure14), nearly 2,000-foot high, is an elegantly tapered structure featuring softly rounded corners. Also, based on the wind tunnel test, small corner cut and recession are very effective to prevent aeroelastic instability for a square prism by increasing the aerodynamic damping, but large corner cut and recession promote the instability at low velocity to reduce the onset velocity of the instability when the damping is small enough. Corner recession is a kind of softening corner to allow wind move smoothly around the building.




Figure 11: Turning torso, Malmo, Sweden, (http://allcity7.com). Figure 12: Proposed Spire tower, Chicago, (http://www.globalconstructionwatch.com). Figure 13: F12. New World Trade Center, New York, (http://www.examiner.com). Figure 14: Wuhan Greenland Center, Nanjing, China, (http://pinterest.com).

## DATA ANALYTICAL STUDY

In this paper, 73 super tall buildings (building with more than 300 (m) tall) built by 2012 will be studied to find out the number, rate and the growth of aerodynamic (geometric) modifications. In this study, the geometry of the buildings was simplified and also for instance if a building like Shanghai financial tower has tapering and opening together, both of these aerodynamic (geometric) modifications are considered. In (Figure15) and (Figure16) the number of super tall buildings in macro and micro level of modifications will be shown.

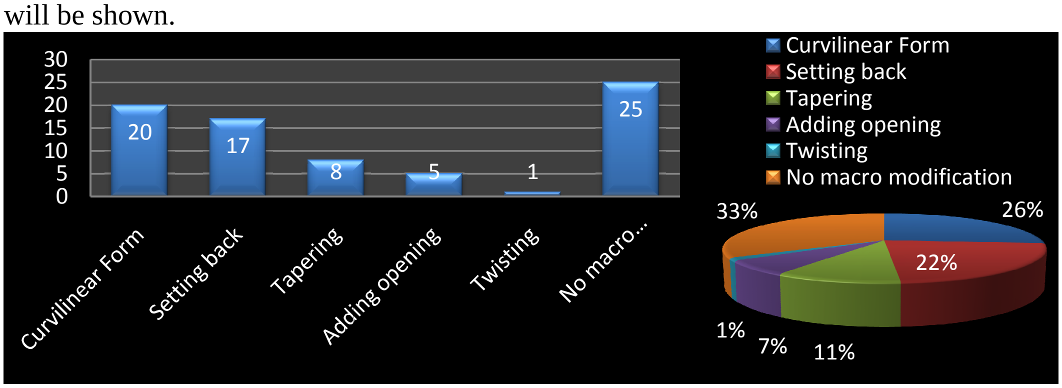


Figure 15: The number and the rate of super tall buildings regarding to the geometry and form

Based on the (Figure15&16), there are two interesting findings; the first is the number of super tall buildings without utilizing any type of this concept and the second one is the rapid increasing of the number of buildings with curvilinear form in the past decade. As the effect of this concept on a building can simply check with CFD software and wind tunnel test, inattention to this architectural strategy cannot be a rational and logical professional work. In (Figure17) buildings will also be divided into three main divisions based on the micro aerodynamic (geometric) modifications: corner recession, corner roundness and corner cut. Again, the number of super tall buildings without using this concept is amazing.

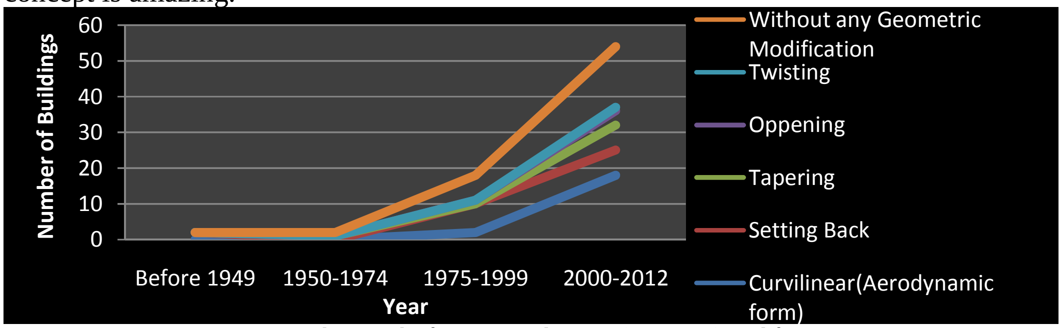


Figure 16: The growth of macro aerodynamic (geometric) modifications

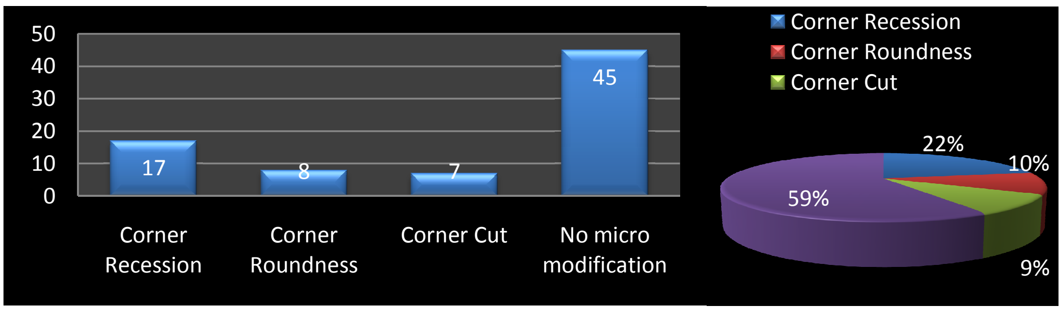


Figure 17: The number and the rate of super tall buildings regarding to micro aerodynamic modifications

## CONCLUSION

In design of tall buildings, as one of the close architectural-structural realm, architects not only by designing aesthetically, but also by choosing the shape, form, and geometry regarding to the structural parameters like dynamic effect and consequently dynamic response of tall buildings can play an important role. Unlike stiffening structures and adding dampers architects by designing aerodynamic forms and even by aerodynamic modifications like tapering and corner modifications can achieve these goals as a precautionary method. Unfortunately, these simple modifications have not implemented in most of the tall buildings; hence, the structural efficiency that is dependent on the weight of the structural material will be decreased.

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# MATERIAL CONDITION AND DETERIORATION ASSESSMENT PROGRAM FOR A 3RD CENTURY ROMAN TEMPLE

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## ABSTRACT

*Antioch ad Cragum* is an ancient Roman city on the southern Mediterranean coast of Turkey. Erdogmus and a team of archaeologists have been studying the collapsed, ruinous temple of the city since 2005 with the ultimate goal of reconstructing it partially as a historic site. The *Temple of Antioch* is designated as a Corinthian order, pro-style, platform temple based on the blocks found and studied. The super structure is dry stack masonry, while the foundation is mortared rubble masonry. Samples from mortar in the foundation walls and base were collected for laboratory analysis and findings on this were published previously. During the fieldwork season of 2011, with the consultations of Freedland, detailed assessments on the condition and deterioration of the temple's marble blocks were started. Following were among the detected deterioration causes: lichen (white, black, and orange species), algae, moss, alveolization, white residue, minor surface cracks, and major structural cracks. Furthermore, a novel, nondestructive, quantitative block assessment tool is being developed. The paper presents: methods used to identify the types and extent of damage on the marble blocks; the development of a damage identification booklet, block assessment forms, and block database specific to the project; and some experiments conducted to assess the materials and the deterioration mechanism. The project's conservation efforts are still in its early stages, therefore, future plans are also presented.

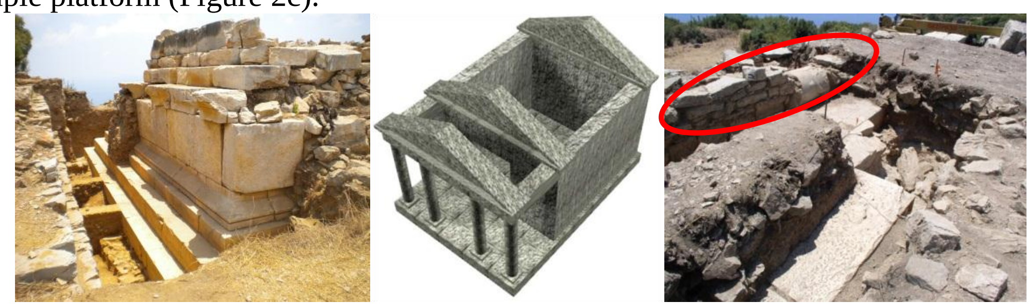
## INTRODUCTION

*Antiocheia ad Cragum* was one of the larger Roman cities of the Mediterranean coast region of modern Turkey known in antiquity as *Rough Cilicia*. This city was founded in the middle of the 1st century A.D. and was an important provincial coastal city of the Roman Empire at the time. The ancient city, now in a state of ruin, includes an imperial temple (henceforth referred to as the *Temple of Antioch*), which was first identified by archaeologists in the 1960s. It remained in this ruinous state until it was re-discovered (under heavy vegetation) by the archeologists of this project during a 10-year long surface survey project in the late 1990's (Figure 1a). With the encouragement of the local government, the same archeologists started a new project in 2005, specifically geared toward the potential reconstruction of the *Temple of Antioch*, and invited Erdogmus to take the role of the project's leading architectural engineer. Over the last 7 years of field work, the fallen temple blocks have been moved to nearby fields using heavy construction cranes and carefully laid on wooden slats (Figure 1b), ready for further study, conservation, strengthening, and eventual re-use for the reconstruction.

**(a)** **(b)**

***Figure 1. Temple of Antioch* Site Photos.** a) Initial status of the temple after the clearing of vegetation, b) Block field aerial view

As the blocks were removed by the engineering team, the archeology team was able to progress with the excavation around the temple platform (Figure 2a). Through a study of the elements discovered on site and a strong collaboration between the architectural engineering and the archeology/art history team, a hypothesized and rough architecture of the *Temple of Antioch* was realized (Figure 2b). As the project progressed, the team was also able to identify the construction system a little better, along with a strange deviation from a typical Roman Temple architecture: Byzantine-era tombs constructed on the Temple platform (Figure 2c).



**a)** **b)** **c)**

***Figure 2.* Excavation progress and site investigation findings:** a) Northern wall of the *Temple of Antioch* after excavations (end of 2012 season); b) 3D Rendering of the hypothesized original architecture of the *Temple of Antioch*, c) Byzantine Intervention on the *Temple of Antioch* platform: Byzantine tombs made of reused stone

The *Temple of Antioch*'s construction is formed of a solid Roman concrete foundation and dry-stone (marble) superstructure. The Roman concrete is identified as a 1 (lime): 2.5 (sand) mortar with large aggregate. No pozzolana was found in the mixture. Further details regarding mortar analysis can be found in Erdogmus and Armwood (2008).

This temple offers the unique opportunity to research what is likely to be a completely preserved, albeit collapsed, building. Such a study, however, is a challenge for both the engineering and art history/archaeology disciplines, as it includes more unknowns than available information. This paper covers a very small portion of this long-term and interdisciplinary project. More specifically, this paper covers the condition assessment work done during summer 2011 and academic year of 2011/2012.

## TEMPLE BLOCK CONDITION ASSESSMENTS

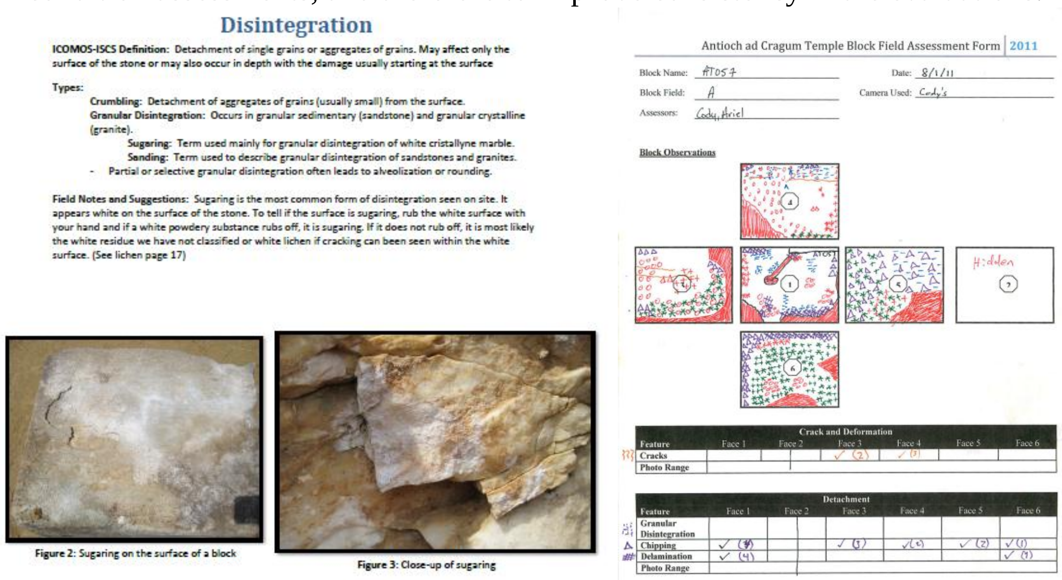
The date of the *Temple of Antioch*'s collapse is unknown; however, the result was a heap of blocks strewn about the foundation walls and over the platform (Figure 1a). The team documented over 600 blocks (excluding smaller fragments) by the end of the summer 2012 season at the temple site. While a few fallen blocks remain at their as-collapsed location, the majority of the blocks have been relocated to the block fields nearby the temple for more thorough documentation (Figure 1b). Further, some blocks have been identified in nearby burial grounds. It is likely that more of the *Temple of Antioch* blocks have been previously removed from the site. All of these blocks have various types of damage and deterioration due to: initial collapse/impact; sustained point load after collapse (block on block, see Figure 1a); weathering, vegetation and other biological growth; and erosion due to water, winds, and other environmental and time related effects. The engineering team for this project is also in charge of managing the conservation efforts since the two endeavors are closely related. For the eventual partial reconstruction, the blocks will undergo a variety of conservation efforts and structural repairs including cleaning, repair of cracks, and strengthening. Successful conservation and structural retrofit interventions require identification of the types and causes of deterioration as well as extent of damage. Thus, the team's current focus is on identifying the causes and extent of the different types of distress on the Temple blocks through *in-situ* assessments and laboratory testing.

### *In-situ visual block condition assessments*

This project is challenging in terms of condition assessments due to:

- Unknown material origin (unknown quarry)
- Unknown initial, undamaged material properties
- Only approximate knowledge on date of construction (estimated based on stylistic and historical evidence and knowledge)
- No information on the date and cause of collapse
- No information on the history of the site after the initial collapse (fires, floods, etc…)

Furthermore, the main workforce on this low-budget project is composed of students, who are asked to help the team leaders with the assessment of the condition of the blocks as they are moved to the block field or for deterioration propagation from year to year. Since the students change every year, inconsistencies in the visual assessments of the blocks were observed and this necessitated the development of a project specific assessment standard. The *Temple of Antioch Block Assessment Protocol (TABAP)* consists of: a documentation manual, field documentation forms, and a hyper-linked Microsoft excel database. The documentation manual was adapted from the *2008 International Council on Monuments and Sites – International Scientific Committee for Stone (ICOMOS-ISCS) Illustrated Glossary on Stone Deterioration Patterns* (ICOMOS 2008). The ICOMOS-ISCS handbook contains illustrated examples and definitions of stone deterioration patterns that have been known to affect stone monuments and sites. With the handbook on site, efforts were made to identify common deterioration patterns present on the temple blocks. This allowed team members to create a project specific glossary, used in TABAP, based on industry standards. An excerpt from the manual can be seen in Figure 3a. Each deterioration pattern in the handbook is described using the ICOMOS-ISCS definition, field observations, and project specific picture(s). The modified glossary will be available to the team members on-site for reference during the block condition assessments, and therefore to improve consistency in the evaluations.




**a)** **b)**

***Figure 3.*** **TABAP Documents.** a) TABAP Manual. A page from the Temple Block Assessment Manual used for visual block assessments; b) Sample page out of the TABAP Field Documentation Forms, filled out by a student *in-situ*.

The field documentation forms are used to log photographs during the site assessments for subsequent addition to the excel database. The form is designed to prompt the user to take specific notes for each face of the block. A form filled out by a student *in-situ* can be seen in Figure 3b. The legend to the left of the tables is created for the user to place color-coded and location specific marks on the orthographic drawings of each block face. Efforts toward the design of a unique fillable digital software application version of the assessment form are underway. Such an application means that the forms can be completed digitally in real time and linked to the database, thus reducing the post-processing time. Finally, the database is used to organize data and files for all blocks. This data is utilized in subsequent interpretations of “block health”, which is the foundation for planning the reconstruction and conservation treatments. The database lists blocks excavated from the *Temple of Antioch* site with detailed information about each block including hyperlinks to pictures and field assessments of the blocks. Information from the database also can be used to perform statistical analyses on the block data, such as percent occurrences of common types of deterioration. For example, at the end of summer of 2011, the number of blocks affected by the four most common deterioration patterns: white lichen, black lichen, white residue, and algae were extracted from the database (Table 1). With the handbook, assessment form, and database, TABAP has created a consistent means of visual site evaluation for the Temple of Antioch project. Eventually, when all of the data and assessments are completed, and information collected by the engineering and archeology teams are converged in this database, the user will be able to identify patterns of deterioration. For example, the user will be able to understand which face of the block has the worst damage with respect to the block's orientation when it was found. This may lead the team to understand some of the history, such as whether or not the damage occurred before or after the collapse.

***Table 1.*** Common Deterioration Types for the *Temple of Antioch*.

| Deterioration Pattern | % of Blocks Affected |
|---|---|
| **White lichen** | 56.8 |
| **Black lichen** | 47.1 |
| **White Residue** | 49.0 |
| **Algae** | 77.7 |

As a general summary to the visual assessments thus far, it should be noted that the quality of the marble used in the *Temple of Antioch* is found to be relatively poor, lacking strong physical characteristics and with inclusions and natural faults.

### *Laboratory Testing*

Limited testing was conducted on small samples removed from the site for laboratory analysis. Scrapings removed in the field from the stone blocks were examined using polarized light microscopy, which is valuable tool to identify minerals based on their optical properties. In addition, handheld x-ray fluorescence was used to examine stone and fragment samples. Handheld x-ray fluorescence (XRF) is a technique allowing non-destructive elemental analysis of materials. The surface to be analyzed is irradiated with x-rays, resulting in the production of fluorescent x-rays, which are characteristic of the elements present. While not capable of identifying all elements, handheld XRF can identify many of the common elements found in inorganic building materials. Based on the limited analysis, the white residue appears to be organic growth rather than a crystalline deposit. The XRF also indicated some silicate based minerals in the stone, likely secondary minerals. Further analysis using thin sections of the stone is planned to further characterize the stone, identify secondary minerals, and identify decay mechanisms. Analysis of the mortars has been completed previously (Erdogmus and Armwood 2008) using wet chemical analysis. Further analysis of mortar will include utilizing thin sections on samples collected from different parts of the temple for the comparison of mortars from elements that may represent different construction periods (Ancient Roman versus Byzantine era, for example).

## NON-DESTRUCTIVE EVALUATION

Three nondestructive evaluation (NDE) techniques were utilized on the *Temple of Antioch* site to better understand the condition of the site and the elements: ground penetrating radar (GPR), fiberscope remote inspection, and impact-echo. The first two of these methods were employed to assess the site and will be briefly mentioned here, while the third method was utilized to perform condition assessments on the blocks and will be explained in more detail later in the paper.

### *Ground-penetrating radar applications on the Temple platform*

Local residents revealed a common belief that there is a vaulted chamber located underneath the temple platform. Given the fact that several common-era buildings in the area have such vaulted chambers and the fact that the *Temple of Antioch* is raised more than a floor height above the modern ground surface, this hypothesis was certainly plausible. Excavation of the temple mound revealed the extents of the platform and its foundation walls to a depth of more than three meters. In addition, a trench on top of the temple mound revealed a void in the platform that showed signs of a barrel vault. Since such observations during excavation seemed to support the theory of a vaulted chamber, the platform was scanned with GPR. The challenges of the site (heterogeneous soil, uneven surface, extremely small surface areas to scan, numerous unknowns in terms of layers, materials, and depth) made the interpretation of GPR scans very challenging and inconclusive.

***Fiberscope remote inspections on the Temple platform***

To supplement the GPR data, a fiberscope was also used on site. This piece of equipment, a flexible borescope with a small fiber-optic video camera, was used to explore openings to investigate the possible presence of a vaulted chamber and to assess safety conditions before each excavation stage. Prior to the 2011 season, the fiberscope was unable to actually view any part of the substructure, proving that both the platform and the walls are still structurally intact in their currently exposed parts so that no penetrating holes could be found. However, a broken wooden tool handle, presumably left behind by a looter, was discovered *inside* (*i.e.* between the wythes of stone) the eastern wall. During the 2011 season it became possible to drill a few small (1-2cm in diameter, 50cm in length) holes through the temple platform to aid fiberscope inspection. No evidence of such a chamber could be found. By comparing the depth of the bore hole and the length of the fiberscope camera showing Roman concrete structure all the way through to the depth of the fully exposed backside of the temple, it became clear that there was no vaulted chamber and the Roman builders chose to construct a very tall base for the platform to raise it up high. While the chamber may have provided potentially valuable archaeological finds, the story-tall solid structure under the platform suggests: 1) the Temple was constructed to be exceptionally overbearing, not only on top of a hill overseeing the entire city, but also raised another floor height. It eliminates much doubt that this was in honor of a Roman emperor, who may be visiting via sea at times (Important note here: the nearby Roman town of Selinus houses a ceremonial tomb for Trajan, as Trajan passed away while visiting this seaside town, thus, it is very likely, the city of *Antioch Ad Cragum* was also visited – or hoped to be visited- by the Roman emperors of its time), 2) The structural system of the temple with a tall yet solid substructure changes its behavior during wind and seismic events considerably, and future analyses and design of new construction has to take this into consideration.

***Impact-echo-based condition assessment process***

Many of the nondestructive assessment techniques that can be used for the condition assessment of the *Temple of Antioch* blocks are subjective. Furthermore, it would be not only prohibited (due to historic context), but also counterproductive to destructively test any of the 5-10 metric ton blocks to understand their condition and properties. Therefore, the team decided to innovate a reliable means of block assessment utilizing impact-echo testing. The literature (see Jording 2012 for a detailed literature review) has many other applications of impact-echo for damage detection, thus the authors found promise for the applicability of impact-echo for a more objective measure of the condition of the *Temple of Antioch*'s rectangular, marble wall blocks (Figure 4a).


**a)** **b)**

***Figure 4.*** **Impact-EchoTesting.** a) A wall block from the *Temple of Antioch*, relocated on the block fields; b) Instrumented hammer and accelerometer used in the project shown on the mock block cast in the laboratory

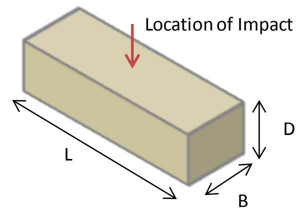
Impact-echo testing uses impact generated stress waves and their propagation to examine the characteristics of various materials and their associated interaction. This NDE method introduces a mechanical impact, typically with an instrumented hammer (Figure 4b), to the specimen and creates an internal stress wave. The induced stress waves are reflected by internal voids, fractures, deposits, or external surfaces, which in return cause displacements on the surface of the specimen. These displacements are measured using accelerometers and recorded via a data acquisition system (dynamic signal analyzer) with respect to time and eventually get transformed into the frequency domain. From this information, the uniformity of the specimen can be obtained by observing predominant frequencies displayed by the specimen in its associated amplitude spectrum. This information can then be used to provide an assessment of the structural integrity.
The building stones at *Antioch Ad Cragum* include various types of elements, which can be roughly categorized as: a) superstructure (frieze, architrave, pediment, geison, etc…) , b) column drums, and c) wall blocks. Therefore, there are many sizes and shapes of blocks. The degree of damage also varies among these types of building blocks. Based on a *rough* visual observation of all block types, the damage levels for the columns is the greatest, superstructure is average, and the wall blocks are in the best condition. Because the wall blocks constitute the majority of the blocks, they are in relatively better condition, and they have relatively homogeneous dimensions (cross-sectional aspect ratios of 1.0); the development of the novel impact-echo-based condition assessment tool is currently focused only on wall blocks. While initially the testing was applied on a select number of wall blocks on site (Figure 4a), the lack of a control specimen and number of unknowns related to material property made it impossible to develop the novel method on the actual blocks. To develop the methodology, a mock block was cast from mortar. The density of the mortar was designed to closely match that of the marble blocks, and the dimensions of the mock block were based on the typical wall block dimensions (Figures 4a and 4b). Impact-echo tests were conducted on the mortar block and compared with a theoretical eigenvalue analysis, previously developed by Sansalone and Streett (1997). The results from the impact-echo testing in the lab were also

correlated to a finite element model (FEM). Errors of 6% and 2.4% were observed when comparing the mortar block results with the theoretical eigenvalue analysis and the FEM, respectively. This correlation allowed for the development of a Real-time Impact-echo Analysis Program (RIAP). RIAP utilizes user input variables, pertaining to the specimen, and outputs the expected frequencies via eigenvalue analysis (Figure 5). Comparisons of the frequency peaks in RIAP with the frequency peaks from impact-echo testing provide the necessary information for structural evaluation.

**Theoretical Fundamental Mode Shapes**

*0.6≤D/B≥2.0 *L≥3(Maximum of D or B)

| | | | | | |
|---|---|---|---|---|---|
| Density (ρ) | 2000 | $kg/m^3$ | Depth (D) | 0.4 | m |
| Poisson's Ratio (v) | 0.25 | | Width(B) | 0.4 | m |
| Modulus of Elasticity (E) | 2.00E+10 | Pa | Length(L) | 1.5 | m |
| Cp(P-Wave Speed) | 3464.102 | m/s | D/B | 1 | |
| Cs(S-Wave Speed) | 2581.989 | m/s | | | |




| Aspect Ratio D/B | Beta | Fundamental Mode f1 (Hz) | Mode 2 (Hz) | Mode 3 (Hz) | Mode 4 (Hz) | Mode 5 (Hz) | Mode 6 (Hz) |
|---|---|---|---|---|---|---|---|
| 1.00 | 0.87 | 3767 | 5312 | 7158 | 9230 | 10661 | 8815 |

***Figure 5*. RIAP Interface.** RIAP user interface showing the user input and the expected response output

The comparisons between impact-echo testing, theoretical eigenvalue analysis, and finite element modeling coupled with the development of RIAP provide engineering and archaeological research teams with reliable methods to structurally evaluate rectangular stones. Further details of the impact echo process as applied in this project and details of the finite element analysis and RIAP can be found in Jording (2012). With the methodology developed on the mortar blocks, in the next phases of the project, impact echo testing and RIAP will be used on site to assess the metamorphic wall blocks of the *Temple of Antioch* and provide the means for the condition assessment of building blocks. Having a baseline for the "undamaged" block impact echo results will enable users to better rate the ancient blocks.

## BLOCK CLEANING PROCEDURES

As can be seen in Table 1, most of the building blocks present some form of biological growth which accelerates deterioration. Two of the most common forms are algae and lichen, most of which are present on the same blocks simultaneously. While it may be impossible to clean all faces of hundreds of blocks before reconstruction, it is important to clean some of the growth to reduce the rate of further damage of the blocks. Persistent biological growth weakens the stone surface and propagates the cracks that may have been initiated by other means (*i.e.* impact). In other cases, biological growth may cause surface cracks and spalling, or obscure significant decorative carvings. While important for the conservation of the stone, an assessment of the biological growth and its growth rate in the environment is also necessary to develop cleaning recommendations. In the summer of 2011 limited initial cleaning trials were conducted on four blocks. The cleaning chemicals were limited to those readily available in a relatively remote area in Turkey. Three of these are unadorned wall blocks. A relatively less invasive process was also tried on a geison block which was carved with the shape of a turtle. Table 2 lists the block numbers, descriptions, the biological growth problems present, and the cleaning process utilized in 2011.

***Table 2.*** Block Cleaning Trials in 2011 Season

| Block No | Description | Problems | Cleaning Procedure Applied |
|---|---|---|---|
| AT008 | Wall block | Half of surface covered with algae (gray when dry), and spot white lichens on top | Strip cleaned:<br>1. Dry brush<br>2. Spray with distilled water and brush<br>3. Spray with a mixture of 1:3 of sodium hypochlorite: distilled water, wet brush<br>4. Repeat for two days<br>5. Checked one week later: Condition improves.<br>6. Checked one year later. See before and after photos in Figure 6. |
| AT070 | Wall block | Surface mostly white due to larger coverage of white lichen over algae | |
| AT099 | Wall block | Entire surface is gray (covered with algae). White and black lichen on top | |
| AT204 | Decorated geison block | White residue and orange-black discoloration | Tap water soaked towel is placed over the turtle figure, replaced as the towel dries. |

***Figure 6.* Before and After Cleaning-Wall Block .** Left- AT099 before any treatment in 2011, Right- AT099 in 2012, one year after the treatments. It is clear that the algae and lichen was killed with the solution applied, and new growth was successfully avoided.

***Figure 7.*** Turtle molding on block AT204. Left- Before any treatment in 2011, Right- In 2012, one year after the treatments. The picture and light/shade quality of photos make it a little difficult to report, but observations in-situ confirm that there was hardly any change in the condition.

In 2012, the conditions of these treated surfaces were documented (Figures 6 and 7). The cleaning methods utilized for algae and lichen on the wall blocks were successful, but labor intensive. The non-invasive (without brushing) process used for the turtle molding, however, was not very effective. In the future, other cleaning techniques will be tried when the import of cleaning chemicals can be conducted. Removal of the white residue and the orange-black discoloration was unsuccessful.

## CONCLUDING REMARKS AND FUTURE WORK

The investigation of *Temple of Antioch*, with the ultimate goal of a partial reconstruction, is a challenging and comprehensive project that requires strong interdisciplinary cooperation. Fieldwork is performed for about two months each year; while analysis work is conducted year-round. The rotation of the students also makes continuity a challenge. Additionally, the Turkish government has strict requirements for all excavation projects on national heritage sites and yearly renewal of working permits and approvals are needed. Together, these factors lengthen the project duration, such that completion has been tentatively placed for the year 2020.

This paper presents the efforts made in the material condition and deterioration assessment of the remains during the field work of 2011 and academic year of 2011/2012. A standardized block assessment procedure (TABAP) has been created to help bring consistency to the *in-situ* visual assessments. The authors also conducted preliminary laboratory testing to better understand what deterioration mechanisms are affecting the remaining blocks of the temple. Further testing of samples will be conducted as part of the future work. A novel, nondestructive, impact-echo based condition evaluation technique is successfully developed in the laboratory, and it will be used *in-situ* in future seasons to assess the structural health of individual blocks. Preliminary work in cleaning and conservation of the blocks have already begun, however, the authors are working toward more efficient methodologies. Future work on the *Temple of Antioch*, with respect to condition assessment, also includes the development of a novel digital application to streamline the visual assessment process.

## ACKNOWLEDGMENTS

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# EVALUATING THE TRADEOFFS OF OCCUPANT COMFORT AND ENERGY SAVINGS: A STUDY OF WINDOW CONTROL SENSITIVITY

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## ABSTRACT

This paper investigates the tradeoffs between occupant comfort and energy savings for a wide range of control scenarios in several variations of mixed mode buildings. A series of EnergyPlus simulations were conducted for a future university campus building located in Boulder, Colorado. These simulations show that occupant comfort, as defined by ASHRAE, does not correspond to the modeled design with the highest energy savings. A variety of building shell, HVAC and mixed-mode operation schemes were tested to measure energy savings over a baseline building with the energy results juxtaposed against the predicted mean vote as well as the number of hours the cooling setpoint is not met. This paper also highlights some areas where existing standards are not clear in regards to application of adaptive comfort models and the number of hours when a cooling setpoint is not met. EnergyPlus simulations show 5-8% savings for mixed mode design over a sealed building for four types of shell and HVAC configurations. However, when a typical window opening behavior is modeled much of that savings is eroded. This results in concurrent mixed mode design buildings (buildings where HVAC systems are running while windows are open) being less prone to changes in energy use as a consequence of human interaction.

Keywords: thermal comfort; mixed mode buildings; occupant behavior.

## INTRODUCTION

The United States has been making a push toward more energy efficient buildings given pressing environmental concerns. However, balancing energy concerns with thermal comfort is not necessarily straightforward. For example, should you leave the HVAC system running while the windows are open? Or should you be using a changeover system, where the HVAC system shuts down once the windows are opened? This paper seeks to evaluate the tradeoffs of energy savings and occupant comfort. Specifically, this paper is interested in how controlling window openings can affect comfort and energy. The work is intended to guide designers and planners at the University of Colorado in particular, while offering possible guidance for other buildings in similar continental climates. As the campus is striving for more and more energy efficient buildings, so-called mixed mode design offers one important part of a low energy building solution. However, mixed mode design is climate specific; therefore, it is important to investigate mixed mode design in the location where it is intended to be used. Much of the existing literature has focused on moderate California and European climates with building sizes ranging from several thousand square feet to several hundred thousand square feet. The building modeled for this study is an office building located in a dry continental climate with a budget of almost $40 million and projects a gross building square footage of 77,000 feet (7,153 square meters).

## MIXED MODE BUILDINGS

### Overview

"Mixed mode refers to a hybrid approach to space conditioning that uses a combination of natural ventilation from operable windows (either manually or automatically controlled), and mechanical systems that include air distribution equipment and refrigeration equipment for cooling" (Brager 2008). Control of mixed mode (MM) buildings is typically categorized into one of three approaches: concurrent, changeover, or zoned control. In zoned control, a building is divided into different space types and certain zones are conditioned with natural ventilation while others employ conventional compression based air conditioning (AC). In changeover control, a given zone may use both conventional AC and natural ventilation, and switches between them such that when one system is in use, the other is off. In concurrent MM buildings, both natural ventilation and mechanical ventilation are allowed to occur simultaneously. This third type is potentially the most risky design because without proper control sequencing it can easily lead to overconsumption when HVAC systems try to heat or cool a space that is not isolated from the outdoors.

MM buildings typically incorporate a range of high-performance features (e.g. radiant heating and cooling, active or passive shading systems, and geothermal heat exchangers), and manually operable systems (e.g. windows, blinds, and lights). It is with the knowledge that MM buildings are complex, dynamic, and possibly difficult to effectively control that this paper seeks to evaluate robust control strategies.

### Experience with Mixed Mode Buildings

MM buildings have been shown to increase occupant satisfaction and offer higher indoor air quality (IAQ) and occupant comfort (Brager 2008). This increased satisfaction is often due to occupants' access to operable features such as windows, shading devices, and lighting systems in their working environment. Recent studies have shown that occupants with access to operable windows typically experience greater comfort across a wider band of indoor conditions (Nicol & Humphreys 2010; de Dear & Brager 2002). Yet, the introduction of operable features in a building leads to considerable uncertainty in the performance of the heating, ventilating, and cooling (HVAC) system. Occupant presence and occupant actions on building systems (e.g. windows, blinds, and lights) change the internal, solar and infiltration loads of the building and thus the conditioning requirements.

Conventionally, mixed mode design does not cover concepts that are fully conditioned where windows can be opened; rather, it refers to buildings where natural ventilation is the "primary cooling and ventilation system." (McConahey 2008). Within the framework of mixed mode design it is important to differentiate between natural ventilation for cooling and natural ventilation for indoor air quality (IAQ). Typically when a mixed mode building is not operating in a natural ventilation mode, it has to adhere to traditional comfort criteria.

A mixed-mode building is not necessarily transportable from one climate to another. It must be designed specifically for its location (Heiselberg 1999) and a particular goal of the design process is to integrate the building with its climate. Often natural ventilation strategies are used as one component of a low energy building design. For example, buildings in very moderate climates would have a shell that maximizes airflow, while the shell in a cold climate has to balance summer ventilation needs with winter heating concerns. It is clear from a broad range of literature that a moderate climate is one of the most important factors that drives the ability to implement mixed mode designs. McConahey (2008) cites reasonable climatic factors for mixed mode design as: locations with at least 6 months per year with monthly mean temperatures between 0°C and 26.6°C, 30% of occupied hours are between 15.5°C and 26.6°C, afternoon temperatures regularly below 26.6°C, and on the hottest days diurnal swings that drop below 18.3°C for at least 8 hours.

## Control of Mixed Mode Buildings

One of the factors in determining the appropriate control strategy is the primary goal of mixed mode design. A building can be optimized to take advantage of different benefits from mixed mode design including thermal comfort, indoor air quality (IAQ) or energy savings. Often these factors can compete with each other, so setting a priority for the building can help clarify the type of control desired. As for the best type of control Brager, Borgeson and Lee (2009) suggest "there is not yet consensus on whether or when simpler manual control systems are preferable to more sophisticated advanced control systems. The advanced controls have the advantage of being more predictable and potentially closer to the theoretical best operating strategy for a given zone, but the manual controls are typically cheaper, easier to install and operate, often more adaptable, and more likely to support variation in individual comfort criteria".

The same report also offers some guidelines on manual vs. automated windows. For automated windows it is suggested that they be installed in high place where people cannot typically reach the windows, or in places where no one has "ownership" over the window. Manual windows are best located where occupants can have direct control over the window and where they are easily accessible to occupants and maintenance staff. It further suggests that manual windows do not lend themselves to energy savings, but are often much less expensive to install than an optimized fully automatic system. A fully automatic system may come closer to achieving energy savings, but losing the element of individual control deviates from the theory that occupancy control leads to greater thermal comfort. Therefore, there will always be a tradeoff between manual and automatic systems. In general, it is fairly easy to implement manually controlled natural ventilation systems in buildings where there is only one occupant per office. However, complications arise in a shared office space in an open plan design where window openings are controlled by many people.

May-Ostendorp et al. (2011) lays out a method of tuning a building's controls to optimize "free" cooling by using model predictive control (MPC). It is suggested in this paper that a simplified form of the logic derived from the MPC through rule extraction could be embedded into the building control system to help optimize a building's window opening schedule in the future.

Borgeson and Brager (2008) comment on the need for computer models that can account for human behavior in naturally ventilated and mixed mode buildings. They do not present a clear solution for modeling human behavior in mixed mode buildings but suggest "in cases of regimented usage or predictable weather conditions, even simple schedules, coupled with some intuition and common sense, will often approximate occupant behavior well enough to support believable aggregated airflow, comfort, and energy consumption results".

## METHODOLOGY

The overall intention of this paper is to weigh the benefits and risks of a mixed mode building design as they relate to energy and comfort. Specifically, energy will be compared by subjecting the best-case design to a number of control operations and measuring the overall energy use on a per square meter basis. Comfort will be investigated using different metrics at critical times during the summer when mixed mode designs would have the greatest impact on occupant comfort.

The four specific building types to be investigated are:

1) An ASHRAE Appendix G baseline building as outlined by ASHRAE 90.1-2007. This building has minimum efficiency Standard-90.1 compliant, rooftop equipment and lightweight metal stud construction.
2) A building with a shell and HVAC system designed to meet ASHRAE 90.1-2007. The HVAC system is configured as one air handling unit (AHU) per floor with VAV boxes (not fan powered) that have terminal hot water reheat in each zone. The system also has a chiller with a cooling tower. This design was chosen because it is common in this area and around the country.
3) A building with direct and indirect evaporative cooler in place of the chiller and cooling tower.
4) A "best practice" or "best case" building, using low temperature hot water radiant heating, a dedicated outdoor air system (DOAS), passive solar shading, low U-value walls and roof, triple pane windows, high thermal mass (heavy concrete walls and floor) and direct and indirect evaporative coolers for spaces where conditioning is still needed.

In each type of building listed above "typical" methods of natural ventilation will be applied to the building, those are:

1) Sealed building, i.e. a building where the windows do not open, fresh air is provided through the ventilation system. Infiltration comes through cracks in the doors and windows (in particular from the NaturalVentilation object in EnergyPlus).
2) Concurrent MM building where windows are opened and modulate (from fully open, when the indoor and outdoor temperatures are the same, to open just a crack when they are at their maximum difference) when the outdoor temperature ±10ºC away from the setpoint. The key in this condition is that while the HVAC systems are running, the windows are open (it is also important to note that EnergyPlus does not model the interactions between the HVAC fans and airflow pressures, the EnergyPlus users manual states, "The model is restricted to using a constant volume fan [Fan:ConstantVolume and Fan:OnOff] and cannot model variable volume fan equipment." The heat is turned off during the summer (June-August).
3) Changeover MM model, anytime the windows open, the HVAC system for that zone shuts down. Windows can open from 18-24°C (65-75°F) as long as it is not raining. Wind speed is limited to 10 m/s (22 mph). The heat is turned off during the summer (June-August).
4) Nighttime ventilation model, uses principles similar to those above, but only runs from 9:00 pm until 9:00 am and the heat is turned off during the summer.
5) A daytime ventilation model, this is also similar to hybrid and nighttime ventilation, but operates from 9:00 am until 9:00 pm. In this condition, the heat is still available.
6) Following these tests, the "best case" building is controlled to setpoints determined by both the ASHRAE 55 and EN 15251 adaptive comfort standards.

## RESULTS

Figure 1 below shows total energy use grouped by building type. A general observation is that buildings with direct and indirect evaporative cooling save a significant amount of energy over buildings that are cooled with direct expansion (DX) units and chillers. In most cases, the mixed mode control scheme or the night ventilation control scheme shows 5-8% savings over a sealed building. It should be noted that this is not an optimized control scheme. With optimal controls on mechanically operated windows, a mixed mode design would likely show even more savings. Also notable about this series of simulations is that there is not a significant difference between sealed and concurrent buildings. Partially responsible for this effect is that the windows are modulating to ±10ºC of the set point. That is, when the outdoor temperature is exactly the same as the setpoint the window is fully open and when the outside temperature is 10ºC different than the outside temperature the window is only open a small crack. It is highly unlikely that human occupants would ever operate windows with such precision.

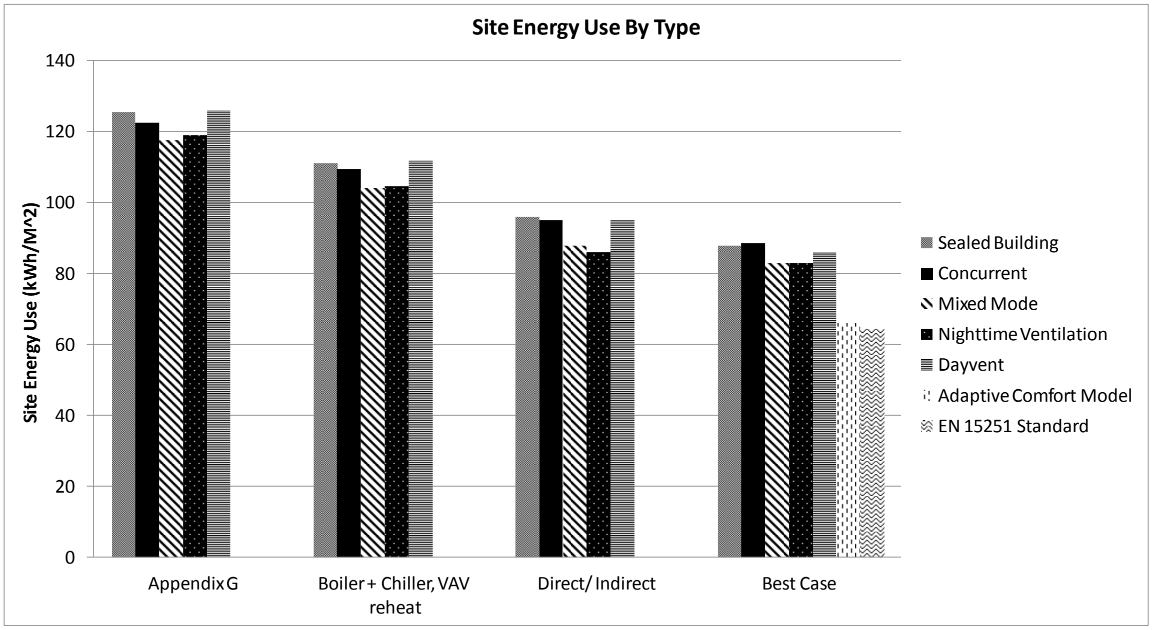


*Figure 1: Site Energy Use by Building Type*

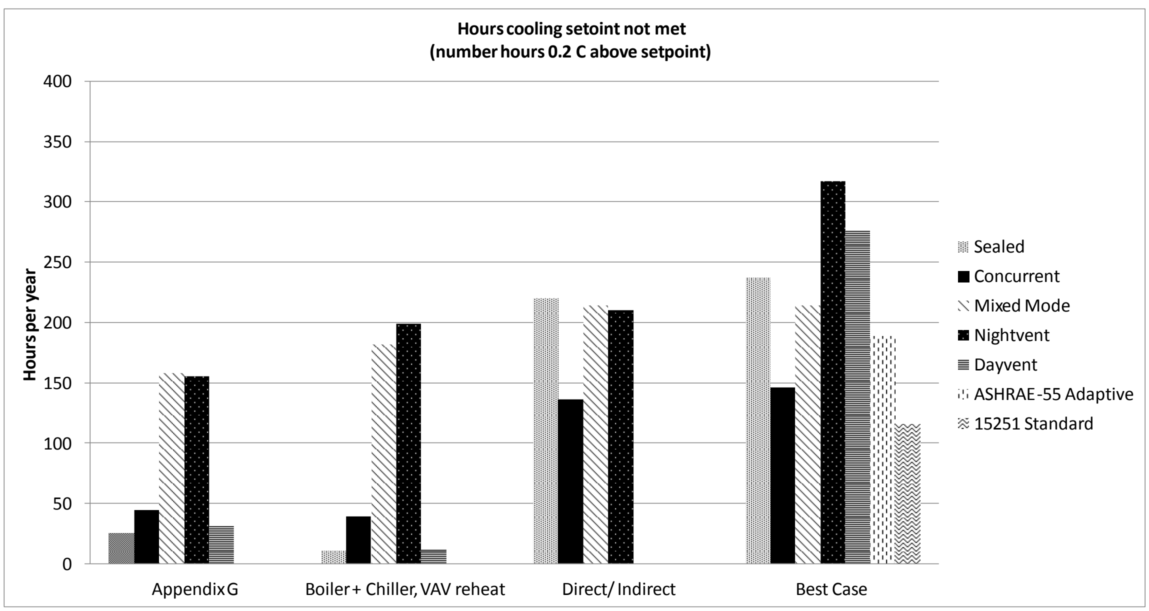


*Figure 2: Number Of Hours When The Cooling Setpoint Is Not Met*

Figure 2 shows the number of hours when the cooling setpoint is not met for all simulations. There is a clear jump in the number of hours when switching to a direct and indirect evaporative cooling system. This is likely because of a limited capacity in the system on the hottest days of the year. It is interesting to note that the concurrent building performs well in the best case building and in the direct and indirect condition. The climate on the front range of Colorado justifies the use of direct and indirect evaporative systems. In these situations the concurrent building is the best performer for overall comfort.

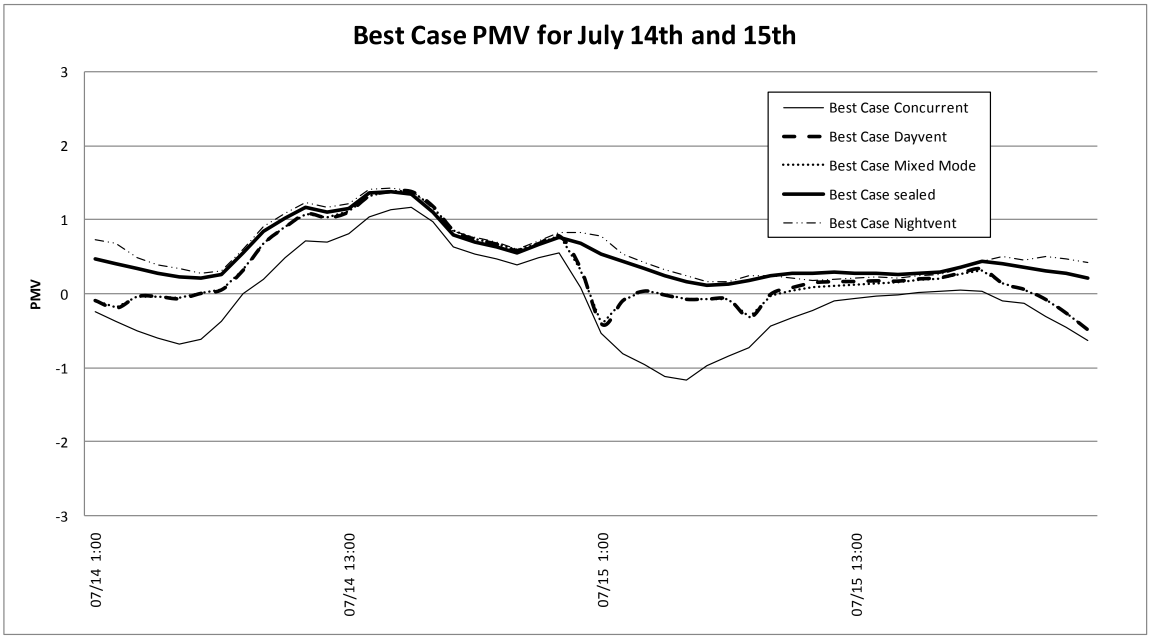


*Figure 3: PMV Results for July 14th and 15th For The Best Case Building*

Figure 3 shows the PMV results for the hottest day of the year. This illustrates that during the day the concurrent building has the best PMV results (closest to thermal neutrality). The other buildings investigated showed very similar results for each type of building.

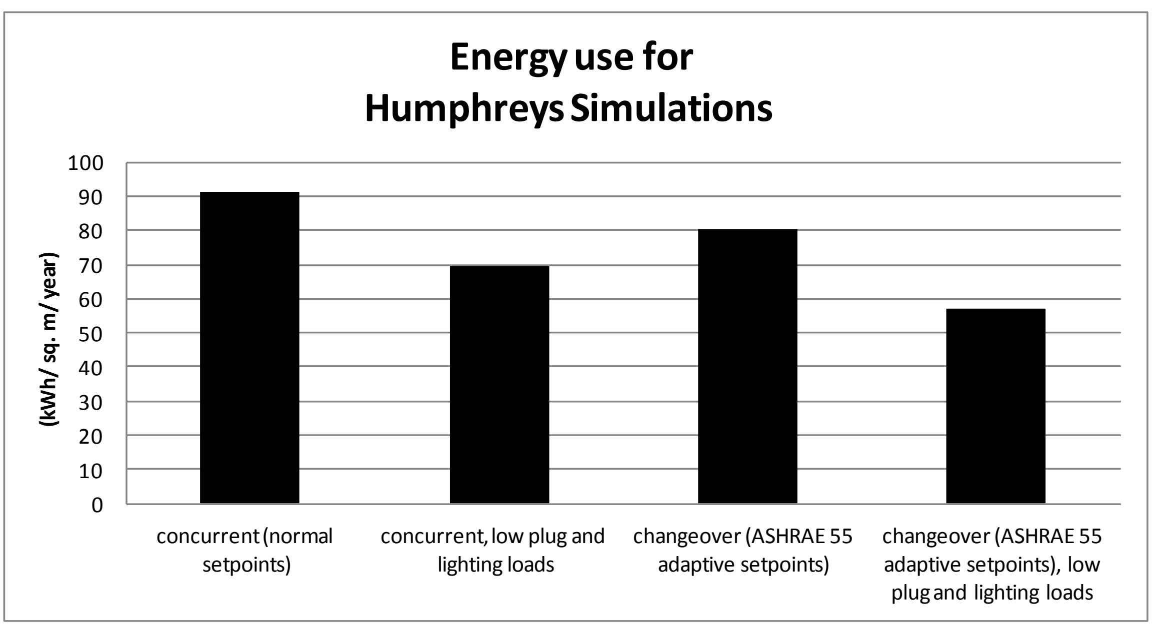


*Figure 4: Energy use for Humphreys simulations showing normalized annual energy use*

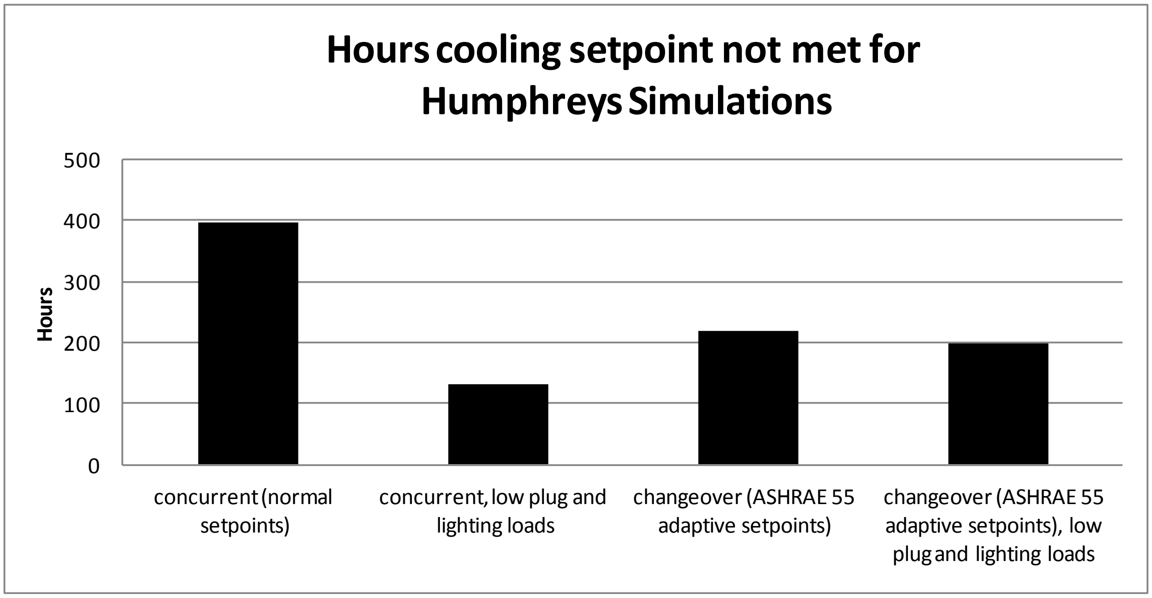


*Figure* 5: *Humphreys simulations hours the cooling setpoint is not met*

Figures 4 and 5 show simulations run for the best case mixed mode building with ASHRAE 55 adaptive setpoints assuming typical window opening behavior by the occupants. The Humphreys model described in Rijal (2008) accounts for the mean human window opening behavior and is implemented through the EnergyPlus Energy Management System (EMS). These results are significant because they show that the mixed mode changeover building increases in energy use by 22% when it reflects mean human behavior. This seems to indicate that human behavior will have less of an energy impact on a concurrent building. Initial simulations showed that lighting and plug loads represent a significant portion of the buildings energy use. These simulations were rerun with lower plug loads to test the effect on the number of hours the cooling setpoint is not met. These simulations clearly show lowering the internal gains can have not only a positive energy impact, but on thermal comfort as well. This is critical because the climate on the front range of Colorado has only a few days of year when it is too hot for direct and indirect evaporative to function well. For this system to function well, internal gains for lighting and plug loads must be kept at or below 9 $W/m^2$.

## DISCUSSION AND CONCLUSIONS

It is clear from the data presented that there is no perfect solution in trying to control window openings in a building. Recent literature suggests that giving occupants control over their own thermal environment is critical in the perceived thermal comfort in buildings. In buildings where windows can be controlled by occupants an important consideration is whether to leave the HVAC systems running while the windows are open or, install a window interlock that shuts down the mechanical systems when occupants open the windows. The simulations shown in this paper reveal ~5% energy penalty for not installing a window interlock. However, it is interesting to note that the models simulating mean human window opening behavior show that a system where windows can open while the HVAC systems are running may be a more robust system. This could ultimately be one of the most important factors in choosing a window control strategy. It seems very intuitive that a building where the HVAC system is running and the windows are allowed to open would consume more energy. However, it is more difficult to predict what type of building will be best for the occupants. PMV, hours that the cooling setpoint is not met and $CO_2$ concentrations go a long way to indicating comfort and indoor air quality in a building. Although there is a vast body of literature out there that suggests there are psychological factors that cannot be captured in computer simulations. One point that turns up again and again is that people like to be in control of their own thermal environment. Each building owner's requirements will be different and often that means maximum energy savings. However, a small tradeoff in savings may well be worth the additional thermal comfort.

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# HOUSING AND SOCIETY: NEED FOR PROGRESSIVE SUSTAINABILITY INDICATORS FOR SOCIETAL SUSTAINABILITY.

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## ABSTRACT

The current consumption pattern of natural resources is unsustainable. The industrial society is following the trend of overconsumption which has clearly led to depletion of natural resources and climate change. The real challenge is to provide a higher “quality of life” with limited “biocapacity” of the earth system. The UK government have implemented effective strategies and policies for sustainable development which include transition towards a low carbon economy; establishment of a legal framework for adaptation of climate change; and place obligations on the generators to increase energy efficiency measures. Eventually, a national standard for sustainable housing, the “Code for Sustainable Homes”; and an innovative programme to make existing houses more energy efficient, the “Green Deal” has been launched.

Accredited “sustainable houses” are looked upon to play a significant role in transition towards sustainability. The socio-technical sustainable transition include processes such as nurturing “niche” products in protected spaces; ‘farming’ niches to build resource capacity; and finally translating niches into a sustainable socio-technical regime. Successful ‘experimental projects’ for sustainable housing have already contributed towards the development of innovative technologies; and produced supporting actors with need expertise. However, consumers being the main decision maker and ultimate administrator of the ‘operational’ phase of these projects’ life cycles, the success of the projects would finally lie in the way they adopt the technologies and contribute in farming niches for sustainable housing regime.

The paper examines the challenges faced in mainstreaming housing sustainability. It discusses sustainable housing, rating systems and sustainability indicators used in assessing housing sustainability with exemplar “the Code for Sustainable Homes” and the “Green Deal” programme in UK. The quality analysis of the extant literature explores transition processes involved in mainstreaming sustainable housing and identifies a number of barriers in the process of absolute transmission to sustainable housing regime. The paper concludes with several suggestions for farming characterised niches required for driving societal sustainability in UK.

## KEYWORDS

Code for Sustainable Home; Green Deal; housing sustainability; socio-technical transition; sustainability indicator

## INTRODUCTION

A number of studies have compared current consumption patterns of natural resources using various units, scales and geographic distribution and found unsustainable trends of natural resource use since $18^{th}$ century (Fischer-Kowlski *et al*., 1997; Behrens *et al.*, 2007; Weisz *et al.,* 2006; Ravallion *et al.,* 2008; WWF, 2008). The trend of overconsumption in today's industrial society (SERI, GLOBAL 2000, Friends of the Earth Europe, 2009) has clearly led to depletion of natural resources and climate change (UNEP, 2007). Whilst the ecosystem existing with its limited "biocapacity" (WWF, 2008), the real challenge is to understand, analyse and direct human actions towards the sustainable development and provide a higher "quality of life" to every one (Netherlands Environment Assessment Agency, RIVM, 2004) without doing any further environmental damage to the earth system. The UK government has recognised the need to become energy efficient more than ever for the delivery of sustainable development. The government has stimulated an array of actions through the Climate Change Act, 2008 (OPSI, 2008), which has manifested in the macro-level policies and strategies reforms aligned to sustainability targets: 80% of emissions reduction; transition towards a low carbon economy; establishment of a legal framework for adaptation of climate change; minimise waste and increase recycling; and place obligations on the generators to increase energy efficiency measures (Department of Energy and Climate Change (DECC), 2009). Following that, the Energy Act 2011 (OPSI, 2011) has been introduced to implement energy efficiency measures in housing and an innovative financial mechanism programme called the "Green Deal" has been introduced to make housing more energy efficient.

"Sustainable houses" are the artefacts of socio-technical housing industry regime (Guy, 2006). According to the Energy performance of the Building Directive (EU, 2010), sustainable housing should be "low carbon" in the terms of consuming energy as well as emitting carbon emissions, compared to the traditional housing. Sustainable housing can play a significant role in transition towards sustainability (Lopes *et al.*, 2011; Pitt *et al.,* 2009). The socio-technical transition theory suggests that the macro-level targets such as zero emissions housing in UK by 2050 (DECC, 2010) can be achieved by nurturing 'niche' products in the form of 'experimental projects' within the existing socio-technical systems (Geels, 2002). Niches should be allowed to grow in protected spaces and build resource capacity. Niches can then be translated into a new socio-technical regime with requires sustainability characteristics and supported socio-technical structures (Rip and Kemp, 1998; Geels, 2002). The 'niche formation' initiated with 'experimental projects' for "The Code for Sustainable Homes" ('the code') (Department of Communities and Local Government (DCLG), 2010; 2011) and the "Green Deal" (see examples on Decent Homes (NAO, 2010)) have successfully contributed towards innovative and retrofit technologies required for the new and existing housing respectively. These projects have also been successful in encouraging innovative actors: developers, designers, architects and others for 'the code' housing (DCLG, 2010); and contemporary actors: accredited assessors, provider and installer (DECC, 2011) for the delivery of the "Green Deal" programme. However, consumers being the main decision maker and ultimate administrator of the "operational" phase of these projects' life cycles, the success of the projects would finally lie in the way they adopt the technologies and their role would have influence on reducing carbon emissions (Thakore and Goulding, 2012).

Unlike 'the code' housing, the market mechanism for the "Green Deal" programme allows the consumer to implement energy efficiency measures at no upfront cost. The "golden rule" is that the cost of measures would be paid through savings reflected in the energy bills resulting from the measures implemented in the retrofitted house (DECC, 2010). The energy-saving measures are typically technical and economical; and the financial mechanism is purely targeted to grow a massive market for energy efficient housing or housing measures. This would lead to techno-economical extension of the existing niches which could be favourable for the environmental sustainability intake to an extent but certainly not to the desired extent for social sustainability. Jensen *et al.* (2012) hold similar views for "the new wave of sustainable housing" in Danish sustainable housing sector and suggests inclusion of larger social structure within socio-technical sustainable housing regime.

Given these issues, the paper explores transition processes involved in mainstreaming sustainable housing in UK, from the process of 'niche formation' with the help of 'experimental projects', to the process of 'farming niches' towards the sustainable regime. Also, drivers for sustainability housing, types of sustainable housing rating tools and sustainability indicators used for assessment and accreditation procedure for the "Code for Sustainable Homes" and the "Green Deal" are reviewed because together, these programmes share a common goal of adopting sustainable technologies and contributing towards the sustainable housing' landscape – zero emission housing in UK by 2050. The qualitative analysis based on published articles, reports, documents and case-studies concerning sustainable housing, identifies a number of barriers in the process of absolute transmission of sustainable housing regime. The paper concludes with several suggestions in 'farming characterised niches' required for driving societal sustainability in UK.

## SUSTAINABLE HOUSING

### Drivers for Sustainable Housing

The present stage of development and the effects of human activities have created global problems that require global decisions. The construction sector, which consumes about 40% of the world electricity, 17% of water; 25% of harvested timber; and produces up to 40% of the global waste and 33% of carbon emissions, contributes to the formation of these global problems (Guarnieri 2008). Demand for new housing has increased due to growth in the world's population; and rapid increase in resource use in developing countries. This growth implies an increase in the consumption of natural resources and generation of waste. Construction can be a source of not only problems but solutions too. The issues such as limited supply, energy use, carbon emissions and safety have already actuated the housing industry to become more efficient (Guy, 2006). In developed countries for more than 20 years of green housing practice, "Green" housing and structures, not only have little potential negative impact on the environment, but also are cost effective. Last two decades have seen advancement and implementation of assessment tools for housing and structures on the environmental, economic and social criteria. Now environmental certifications of housing are widely practiced in many countries.

"Green" housing - is the practice of construction and operation housings, the purpose of which is to reduce the consumption of energy and material resources throughout the life cycle of house: the choice plot to design, construction, operation, repair and destruction. Goal of "green" construction is to reduce the negative impacts of construction activities on the environment and human health for the entire life cycle of the housing through: applying new technologies and approaches; improving green housing products; reducing stress on the regional energy network and increasing reliability of their work; creating new jobs in the field of intellectual production; and reducing the cost of maintenance of housing (World Environment Center, 2012). In 1985, the UN Conference gave a definition of sustainable development as “the ability to meet the needs of the present without compromising the ability of future generations to meet their own needs” (UNFCCC, 1992). "Green" housing have less potential negative impact on environment than traditional housing which can be achieved by an effective and efficient use of resources, the use of alternative resources to conservation, and recycling. Thus the widespread use of "green" housing in the world can be instrumental in societal sustainability.

**Rating Systems for Sustainable Housing**

A number of rating systems in construction and operation of housing have changed the corporate relationship with housing and operating companies for environmental protection and sustainable construction. For example, LEED - Leadership in Energy and Environmental Design was launched by Green Building Council U.S. (USGBC, 2011) to assess the housing in U.S., followed by other popular rating systems such as BREEAM (Building Research Establishments' Environmental Assessment Method) in UK and Europe, and Green Star in Australia. The international certification ensures potential buyers and investors that the housing is "green" and stable. It is highly attractive to tenants and demonstrates corporate social responsibility. Further, many studies support the economic and financial benefits of "green" construction such as optimum cost public services and lower operating costs. "Green" housing are primarily designed to reduce energy and water consumption to 25-30% and 30-50% respectively. "Green" housing has the potential to increase productivity by 1.5%, equivalent to \$1,000/year or \$ 4.05/$m^2$; decrease negative impact on the occupants' health and by sufficiently active penetration of daylight, individual climate control and good visual environment. It has been estimated that the financial advantage of housing with silver certified LEED, is \$35/$m^2$ (Singh et al., 2010; Green Building Council of Australia, 2012).

In UK, housing accounts for 42% of total carbon emissions (DCLG, 2012b). The emissions from housing are evenly distributed throughout the nation (Defra, 2007) and thus it is believed that a systematic nationwide strategy can be effective in reducing carbon emissions (McManus *et al.,* 2010); and increase sustainability in housing. The DCLG, being responsible for housing, planning and housing regulations, recognises its important role in enhancing the “quality of life” without doing further harm to the environment. The DCLG, working with DECC and Department for the Environment, Food and Rural Affairs (Defra) have ambitious plans to address climate change and deliver sustainable development. The mitigation and adaptation measures include supporting people and local communities to become more energy efficient at the earliest; along with setting housing regulations and standards to improve energy efficiency for existing housing; and making new housing developments zero carbon from 2016. The DCLG is promoting the “Code for Sustainable Homes” as a single national standard and housing rating system – assessed and operated by BREEAM (DCLG, 2012b).

**The “Code for Sustainable Homes”**

The “Code for Sustainable Homes” commenced in 2006 and made functional in 2007, is the UK national standard to drive the housing construction industry to produce more sustainable artefacts (houses) through innovative design and construction housing technologies and practices (DCLG, 2010). Currently, ‘the code’ is voluntary except for requirement of level 3 for the new social housing developments funded by Homes and Community Agency (DCLG, 2012b). The housing developments those volunteers to get assessed against ‘the code’ attains the level to which they are certified; and the housing developments those do not opt to get assessed attain “nil certificates” (DCLG, 2009a-c). The housing sustainability is assessed considering the whole house approach including various impacts of the housing on the environment in design and post construction stages. The indicators used are categorised as shown in the Figure 1.

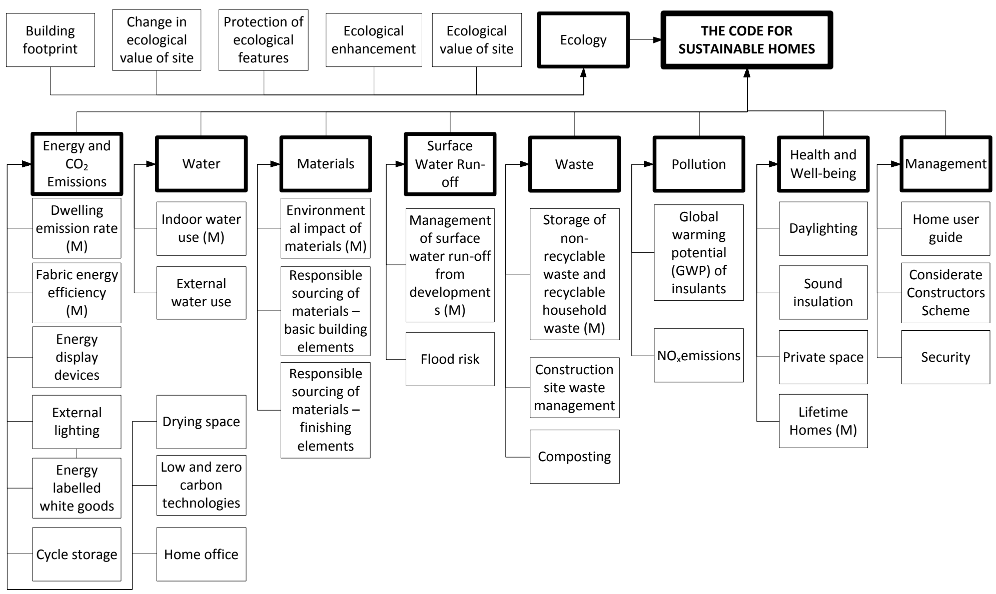


Figure 1: Sustainability indicators used in the “Code for Sustainable Homes”; mandatory requirements are denoted by (M) (Adapted from DCLG, 2010)

A number of ‘the code’ housing projects have gradually grown which include variety of housing types, a range of tenure and procurements types; private sale and social housing units for rent and sale; and a range of design approaches, build systems and construction processes adopted at all scales and sizes, which offer opportunities for learning process. The case studies analysis show that the second time working with code was found easier than the first time; and the projects that adopted ‘the code’ right from the beginning (design stage) were easier to build. The projects were successful in delivering high-quality, highly insulated housing shell; low carbon renewable features; and gaining 10 years housing structural warranty. However, the costs incurred in the housing development projects were very high due to additional costs for materials, systems, features, training and development systems and building up more “sophisticated” supply chain. The experts and industry believe that ‘the code’ is proving to be an important tool in delivering sustainable housing artefacts, though the occupant/consumers’ feedback is very limited (DCLG, 2012b).

**The "Green Deal"**
The UK Government has been challenged to retrofit a huge stock of existing housing to reach the targets of 80% carbon emission reductions by 2050 (DECC, 2009). An initiative called the "Green Deal" is announced by the government that would be functional by October 2012 (DECC, 2012). It is a voluntary government policy with an innovative financial mechanism, allowing the consumer to implement energy efficiency measures compliant to the "Golden Rule" associated with the "Green Deal". The savings in the energy bills resulted from installing energy efficiency measures (see Figure 2) should equate the cost of implementing those measures (DECC, 2011)

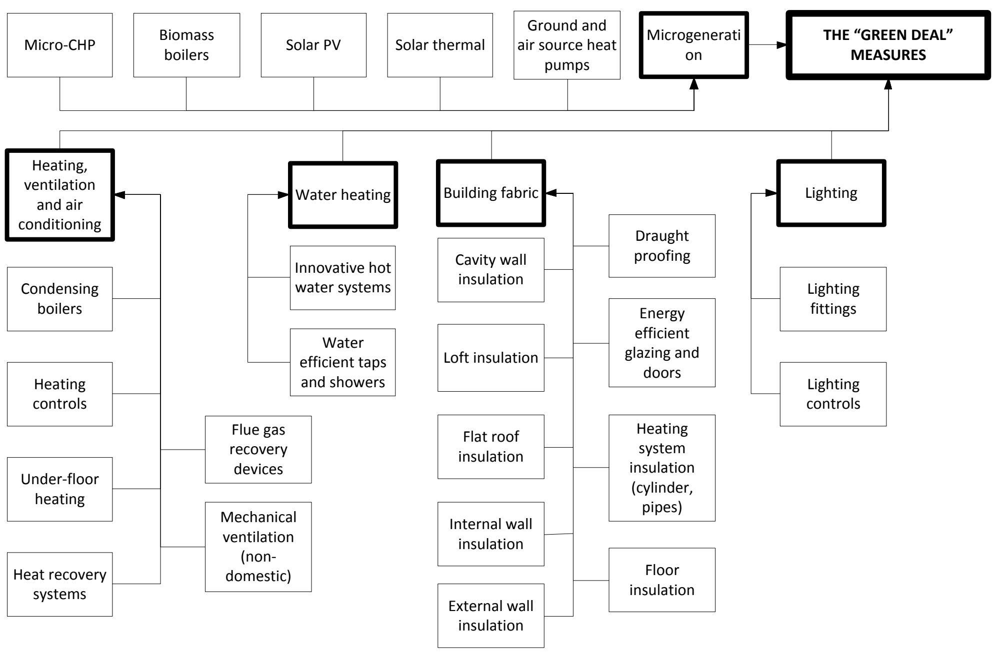

Figure 2: The "Green Deal" retrofitting measures for energy efficiency (DECC, 2007)

The 'experimental projects' such as Warm Front Scheme and the Decent Homes Standards (NAO, 2010) supported by the UK Government and local authorities have demonstrated successful refurbishment and 80% reduction in carbon emissions. They have been successful in generating first- order learning in the form of development of specialist knowledge, energy efficient industrial practices and relevant network (for further details, see Thakore and Goulding, 2012).

## TRNAISITON PROCESSES

Socio-technical regime of sustainable housing is combination of various attributes ranging from hard physical material artefacts to the users' soft social practices depending on the lifestyles adapted for the artefacts (see Figure 3) (Farmer and Guy, 2005; Guy 2006; Lovell *et al.,* 2009) in a locked-in fashion (Rip and Kemp, 1998; Geels, 2002). Such regimes have to undergo profound changes to uproot the existing mutual interdependent technological performance and social practices, which together dictate the characteristics of sustainable socio-technical regimes (Russell and Williams, 2002; Smith *et al.,* 2005; Schot and Geels, 2008).The result of process changes occurring at variety of points of a complex web structures are not in a structured pattern. The radical changes come first from the pioneering actors in supported spaces, developed as a peripheral activity within the regime (Schot, 1998; Geels, 2002; Rip and Kemp, 1998). Practices from these actors are then translated to other actors in different socio-technical situations within the niche and regime, then to other actors and so on to develop higher order characteristics of a sustainable regime (Callon, 1986). When niches are successful, they are farmed to garner wider uptake and become part of the mainstream (Schot *et al.*, 1994; Kemp *et al.*, 1998).

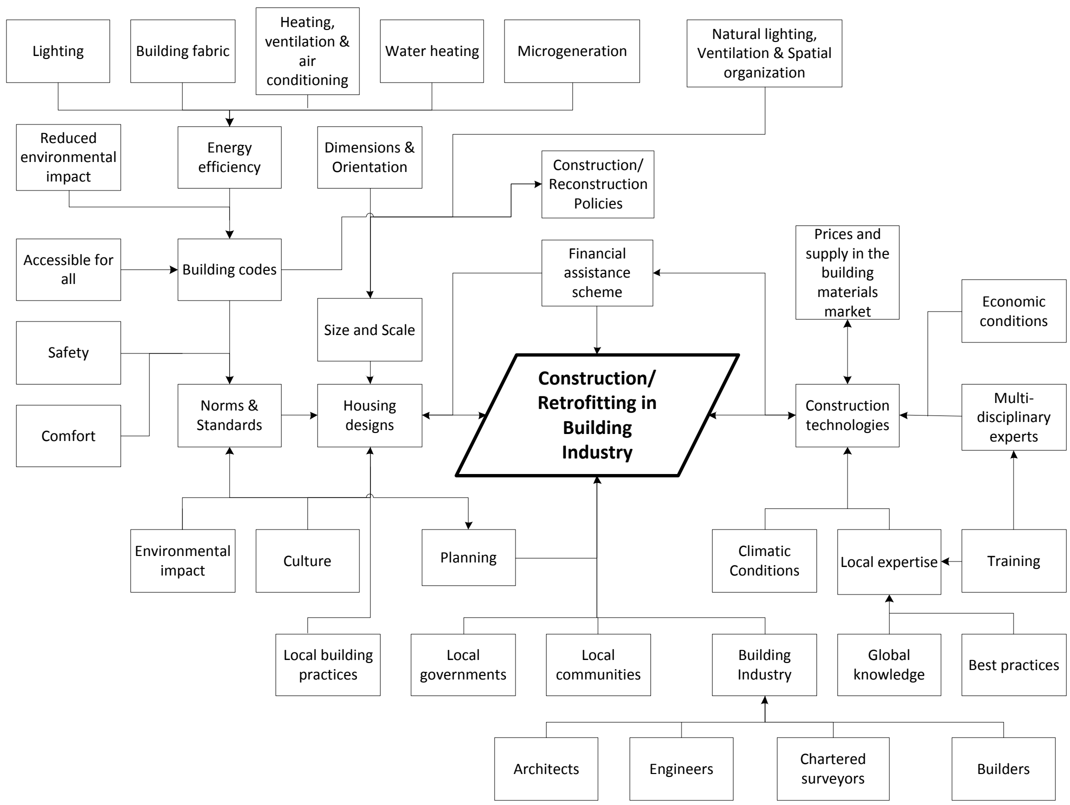


Figure 3: Socio-technical regime for construction/retrofitting in housing industry (Adapted from DECC, 2011; Geels, 2002; Jha *et al.*, 2010).

## Niche Formation

In UK, the sustainable housing 'niche formation' process started 40 years ago, with regulatory system introducing the 1965 Building Regulations (HMSO, 1965), consequently developed as Part L of "the Building Regulations 2010 Conservation of fuel and power" (HMGovernment, 2010). The sustainable housing being guided by resource and energy efficiency, the most affords were/are directed in developing robust practices and techniques in energy and cost saving. This is undoubtedly reflected in the rating system for 'the code' housing where the most weight (21%) is given to the category 'Energy and Carbon Dioxide'. However, the review of 'experimental projects' of 'the code' housing and the "Green Deal" show that the occupants' contribution is limited, though they are the primary actors in the development of these niches (DGCL, 2009; 2010; NAO, 2010). Smith (2007) has identified several contrasting socio-technical dimensions in newly formed niche and regime and states: (1) each dimension is discrete; and (2) each dimension is presented in context of (or in favour of) the new niche or regime and (3) against the existing niche or regime. Having said that, it is suggested that users' relations (practices) essential for high performance of the niches should be appropriately translated to the targeted actors (for example, consumers).

**Niche Farming**

Niche 'farming' (meaning 'further niche growth') essentially constitute of learning processes (Kemp *et al.,* 1998; Hoogma *et al.,* 2002) within successful niches. The second order learning involves actors from the outside of the niche: broad network of users/consumers' behaviour which would shape the performance targets of the technologies developed through the first order learning in innovative technical niches; and contributes towards the new regime formation (Hoogma *et al.,* 2002; Weber *et al.,* 1999). The niche farming is particularly challenged by the users/consumers of the technology and do not allow the niches to play their attributed role in the wider transformation process (Loorbach and Rotmans, 2006). The sustainable housing niches referred in the paper can be said to be 'radical' niches because they involve many structural changes (Smith, 2003). First-order learning such as standardisation of insulation level and water use, has been driven through strict regulations; however these regulations do not stimulate second-order learning. They do not present a holistic state-of-art argument for the societal development and thus fail to raise awareness required for mainstreaming socio-technical regime (Raman and Shove, 2000).

**Adaption and Inclusion**

'The code' housing case studies show that the main driver for the developers of 'the code' housing projects is to meet planning regulations for social housing projects (DCLG, 2010). Other drivers included qualifying for funding, enhancing organisational capacity, remaining at the competitive edge, and using more suitable rating system (Sponge Sustainability Network, 2007). Moreover, developers are rewarded in a short term in the form of financial gains for such initiatives. Contradictorily, consumers are not required to meet any minimum sustainability targets (Williams and Dair, 2007); nor do they have incentives such as low cost or immediate rewards. The consumers have to change their practices to suit new technologies, which is again a barrier for consumers to play an effective role in creating demand/market for housing sustainability. The second-order learning can be made possible by recognising niche-regime differences and contrasting dimensions within niches and regimes. A profound understanding for the values, principles and activities underpinning each practices needed for the new regime should be translated appropriately to various groups of actors including consumers and end users (Smith, 2007). Specific intermediate projects targeted to the learning process for specific users groups would be helpful in adaption and inclusion of practices for mainstreaming niches.

During the "operational" phase of housing, the responsibilities of carrying out repairs and maintenance remain with the landlords; while the privilege of using facilities (equipment and services) is enjoyed by the tenants. The guidance, "How to develop and monitor local performance measures. A guide for tenants and landlords" (Hood and Smedley, 2009) has been developed by HouseMark to help social landlords to assess and manage their performance and deliver core landlord services that are in line with the tenants expectations. The guidance includes an approach to embed "more responsive customer-focused services" representative performance management indicators for increased accountability to tenants. Such already existing mechanisms could be of immediate help in enhancing assessment and monitoring process of critical performance of energy efficiency measures and advocating best practices within the tenant/consumers/end users' group.

The rating systems use sustainability indicators to assess and monitor sustainability aspects implemented through the management and planning activities in a development. "Well-designed" indicators represent sustainability aspects interested to the stakeholders in a quantifiable way. The indicators can be measured and have ability to communicate sustainability performance (Gallopin, 1997). Basic understanding of 'how individual actions cause carbon emissions' should be emphasised into the decision making process and indicators should be provocative in connecting day-to-day decision-making processes with societal sustainable development (Beratan *et al.,* 2004). The indicators included in assessment of 'the code' housing and the "Green Deal" qualified housing are designed for industry experts and are acting as drivers for formation of economic and ecological sustainable niches. Moreover, many of the existing indicators are based on qualitative information; and their application would satisfy compliance with the minimum regulatory requirements without doing much effort. Possible progressive indicators are not included in the list of sustainability indicators used for the assessment of housing sustainability due to reasons such as insufficient knowledge of functional relationship of housing performance; and its sustainability characteristics (Smith, 2007). It is suggested that the indicators providing appropriate information of direct impacts of the actions, such as "tons of $CO_2$ emission/capita/$m^2$ or $m^3$/household/annum" would be useful for individual actors, as well as for the application at upper (regional) level (Lützkendorf and Lorenz, 2006).

The sustainability indicators of 'the code' rating systems, such as water use (Micou *et al.,* 2012); window technology (Mempouo *et al.,* 2010); the UK government's "Standard Assessment Procedure" for assessing the energy performance of dwellings, SAP rating (DCLG, 2012a); sustainability measures, costs and expertise (Williams and Dair, 2007) are subjected to research; and many case studies are presented on DCLG website, however, they do not portrait a complete picture of what actions are required by the consumers to make 'the code' deliver its main aim of increasing resource efficiency in the operational phase. In the "Green Deal" case, a number of studies have analysed various aspects of the "Green Deal" ranging from planning permission for external wall insulation (Elton, 2012) to the cost-effectiveness and the standards for thermal insulation (Thorpe, 2010). Here too, very little research is carried out from the consumers' perspective. There is a lack of infrastructure to support consumers' decision making. Moreover, critics suspect that the "Green Deal" calculations are "flawed" and the assumptions are "too optimist"; and it will take longer to pay off than predicted. For every 1% increase in the cost of finance, energy efficiency measures will have to reduce fuel bills by 7% to meet the Golden Rule (Keepmoat, Sustainable Homes and Parity Projects (2012). These current challenges pose difficulties in facilitating engagement and dialogue for the consumers to play their role in mainstreaming sustainable housing, even though there is a desire to adopt sustainable lifestyle amongst the UK public (Sponge Sustainability Network, 2007).

## CONCLUSION

This paper explored the transition process for mainstreaming housing sustainability. The research revealed that the national standard for newly built housing, the "Code for Sustainable Homes" and innovative initiative for retrofitting existing housing, the "Green Deal" have potential of accelerating the uptake of sustainable housing. The niche formation for these schemes have been successful, however, the 'experimental projects' were natured within the protected spaces i.e. secured finance. Once these schemes are exposed to the market, the difference between privately finance and publicly finance energy efficient measures should be acknowledged. The benefits for the consumers would not be materialised directly in monetary form, instead they would have to be seen as a reduction in the cost for energy bills and increase in housing comforts. It is suggested that consumers should be engaged in 'experimental projects' that would develop social sustainability characteristic niches alongside the economic-technical niches, essential for the sustainable housing regime.

Research findings identify the pivotal causal links and dependencies associated with sustainability indicators. However, these are mainly focused on environmental aspects and industry drivers. There is therefore an exigent need to address the social aspects. Niche 'farming' is proffered as a systematic process supported by favourable planning policies; and other governmental policies to encourage catalytic discourse. This would undoubtedly lead to new regulations affecting individual households which would be instrumental for achieving carbon targets. Given this, the housing associations are challenged to take responsibilities to incorporate trainings and raise concerns of using technologies provided in 'the code' housing such as communal heating system, as well as energy efficient technologies in retrofitted housing qualified under the "Green Deal". This is in line with the thinking of the Department for Communities and Local Government (DCLG, 2010).

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# DEVELOPING A STANDARD ENERGY AUDITING PROCESS FOR PENNSYLVANIA STATE UNIVERSITY
## 2013 Architectural Engineering Institute (AEI) Conference

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## ABSTRACT

With buildings accounting for about 39% of our total energy consumption; it is important that buildings are maintained to continuously operate as efficiently as possible. The Pennsylvania State University has 1,784 buildings which make up over 30 million gross square feet in building space and emitted approximately 550,000 $MTCO_2E$ during the 2011-2012 year. This is a 27.5% reduction from what the University anticipated they would have emitted had it not implemented its reduction strategy plan. While Penn State has invested $40 million to re-commission and retrofit existing buildings at University Park and several of the Commonwealth campuses, there is still more work that can be done to improve the Universities energy performance. The challenge the University faces is in determining how to invest these funds to provide the greatest impact on energy savings.

This paper intends to identify and capture the current energy auditing procedure at Penn State. The research presented will: 1.) Include an examination of the project selection process, availability of useful information and reliance of information in an effort to understand current limitations; 2.) Development of a structured process for future energy audits; and 3.) Identify the key information required to produce an accurate energy audit of an existing facility and determine where BIM can be implemented. The paper will conclude with how this initiative is working to integrate Penn State's Office of Physical Plant's (OPP) Energy and Engineering Group with their Virtual Construction Group to use Building Information Modeling to better track and manage energy data on new and existing facilities at Penn State.

## INTRODUCTION

Recognizing the importance of preserving our environment, and also making an effort to lead by example; Penn State has been very active in the recent sustainable movement. Penn State believes that, ". . . While the results of Penn State's efforts are unique to the University, other large building owners may wish to emulate Penn State's process or adapt it to meet their needs." (Klotz, 2007) As the architecture, engineering and construction (AEC) industry has identified the importance of reducing building energy consumption, Penn State created their own campus wide LEED Policy which has been updated to place emphasis on evolving energy goals.

Penn State has had much success with reducing their energy consumption. However, reduced state funding, increasing energy costs, aging infrastructure and an increase awareness of the negative impacts of greenhouse gas emissions have contribute to the university's desire to set additional energy reduction measures. In order to further reduce energy consumption, Penn State has turned to consultants who often utilized energy modeling simulation tools to predict building energy performance. Like the rest of the AEC industry, Penn State has difficulty trusting the accuracy of the energy simulation tools. While the consultants hired by Penn State to perform energy analysis, often do so using energy simulation tools; Penn State Office of Physical Plant (OPP) does not require their consultants to turn over the energy models as a deliverable. Like the much of the AEC industry, Penn State is experiencing some difficultly moving forward with their energy reduction initiatives.

Having the data that is input into the energy simulation models and being able to host this information in a BIM management software package may be beneficial for Penn State. Properly managed energy data could be utilized by the Operations and Maintenance (O&M) personnel to ensure facilities are operating efficiently. Similarly, better documentation would help with the energy auditing process for building retrofits. Energy auditing is an important part of a retrofit process as it is used to asses existing building conditions and produce recommendations for energy reduction strategies.

## PROBLEM STATEMENT

The average age of a building on Penn State's University Park campus is 35.75 years. This means there are a lot of buildings that like the average U.S. building have, ". . . the potential to reduce its energy costs by approximately 22% through energy efficiency retrofits because most were built prior to 1990 and still use outdated, energy-inefficient technologies and building materials" (Benson, 2011). Compared to projected energy consumption numbers, the university has made progress with reducing overall energy consumption. However, with over 932 buildings on the University Park campus alone and approximately 400,000,000 kWh of electrically used annually to power University Park campus; there remains substantial potential for energy saving.

It is important to note that the difficulties Penn State is experiencing with deciding how to focus their energy reduction efforts is not unique to the university, but rather an industry wide challenge (Benson, 2011). When the university first set their energy conservation goals, there was a limited understanding of how to select buildings and pursue opportunities for energy retrofits. With several years of building energy data and more available research on the topic, it is fitting that a careful examination of Penn State's project selection process be completed. The current selection process was examined in an effort to identify any limitations with the process and also to ensure that the appropriate data is being collected.

Previous to this research effort, Penn State did not have a standardized process outlining the appropriate data to be collected to perform the most effective, valuable energy audits. The typical ASHRAE energy audit process is divided into three audit levels. The three audit levels as defined by ASHRAE are:

1. Level 1: Walk- Through Analysis
2. Level 2: Energy Survey Analysis
3. Level 3: Detailed Analysis of Capital Intensive Modifications

While the process and data captured for each type of audit varies from one company to another the basic purpose of each audit remains the same (Deru et. al., 2011). When deciding what projects Penn State will target for energy retrofits, OPP's Energy and Engineering group typically performs Level 1: Walk-Through Analysis; while the Level 2 and/or Level 3 audits are performed by outside design firms during the planning and design phases of a project.

The development of a structured process would help to streamline the energy auditing process while also producing more consistent energy auditing results. Once buildings are selected for energy based retrofits, Penn State hires an outside consultant to perform a detailed energy analysis. If done properly, energy analysis can add value to a project not only in terms of payback predictions, but also by allowing a building owner to see that the appropriate investigative work has been completed (Waltz, 2000). However, Penn State has struggled to define energy analysis requirements. The research will include a critical analysis of the appropriate energy simulation technology and explore opportunities to better assist Penn State's energy engineering teams in defining energy analysis standards requirements.

The "Energy and Engineering" group within OPP currently face challenges with a lack of accurate record documents for their facilities. Every time OPP wants to evaluate a building for an energy based retrofit upgrades, somebody has to go to that facility and physically collect the building data necessary to perform the appropriate analyses. Penn State has both an "Energy and Engineering" group and a "Virtual Facilities" group. To date these two groups have largely worked independently of one another. However, the Energy and Engineering group could potentially benefit from hosting their information in the BIM software managed by OPP's Virtual Facilities group. This research will examine what information is necessary to produce an accurate energy audit for an existing facility and explore ways to merge the two groups and implement BIM for the Energy and Engineering group at Penn State. The research will also investigate other potential areas, such as operations and maintenance (O&M), where the Energy and Engineering group would benefit from accurate record documentation of their facilities. By merging Penn State's Energy and Engineering group with their Virtual Facilities group, OPP can begin to address some of the issues they have with the lack of accurate record documents and make the appropriate information more accessible when it becomes time to perform an energy analysis.

## RESEARCH METHODOLOGY

Capturing and documenting OPP's audit process and the potential interactions of the data with the BIM initiative was performed as an exploratory study using mixed-methods research. This research included an embedded researcher within the Energy and Engineering group, coupled with a series of face-to-face interviews, focus groups, and observational studies of field audits. A series of semi-structured face-to-face interviews with key members of the OPP's Energy and Engineering group were utilized to determine the current process and key issues with the selection process for energy based retrofit projects and to develop strategies for addressing those issues. Several projects which were undergoing energy audits were identified. The energy auditing process on these projects were observed and documented in detailed so the processes could be captured and mapped. By mapping a "typical" energy auditing process for OPP, a critical analysis of the process could be performed. This mapping exercise also helped to standardize the process for OPP. A series of focus groups were then utilized to verify the accuracy of the process maps. The focus groups were also utilized to identify what type of information the energy and engineering group would benefit the most from including in the BIM software and to develop the appropriate BIM infrastructure for their group.

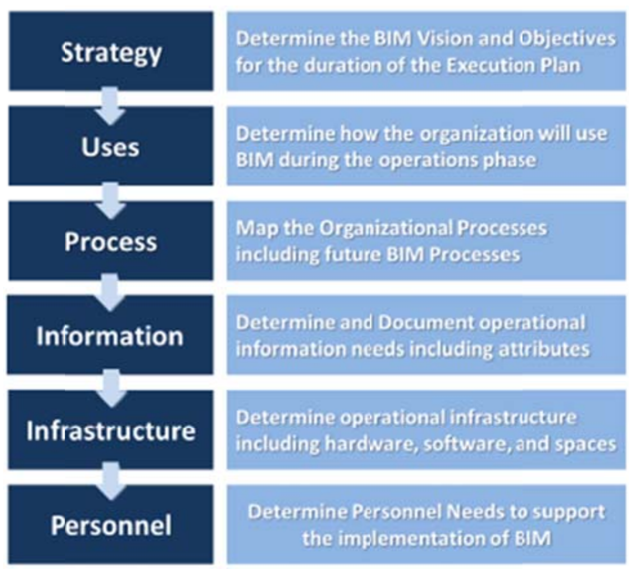



**Figure 1:** The Organizational BIM Execution Planning Procedure (Messner et.al., 2012)

After the research was well underway, it became apparent that research methodology aligned closely with the organizational BIM planning procedure presented in the "BIM for Owners Planning Guide." The Figure 1 shows the six basic steps which are followed when developing a BIM plan for owners. Much like the BIM planning guide suggests, we first sat down determined what OPP's energy goals were and developed a strategy. We then utilized face-to-face interviews to determine how OPP would be utilizing the structured process maps and energy information that was going to be incorporated into the BIM models. OPP's processes were then carefully studied and captured. The focus groups were used to determine the appropriate information and infrastructure requirement needs along with ensuring staff members are aware of their role throughout the process.

## CURRENT CHALLENGES

In an effort to better understand the current processes Penn State's Energy and Engineering group follows to select buildings for energy based retrofit, a series of semi-structured face-to-face interviews with key members from their Energy and Engineering group were conducted. During these interviews, the interviewees were asked to describe the process of how buildings are identified for energy upgrades, the challenges with the current process and the key decision points.

After the initial interviews were conducted, a decision matrix was developed outlining the qualifications needed for a building to be considered for an energy retrofit. Follow up interviews were arranged with each of the original interviewees. The intention of the follow up interviews was to provide validity to the decision selection matrix that had been developed and also to allow the interview participants to have an opportunity to add value to the developed tools.

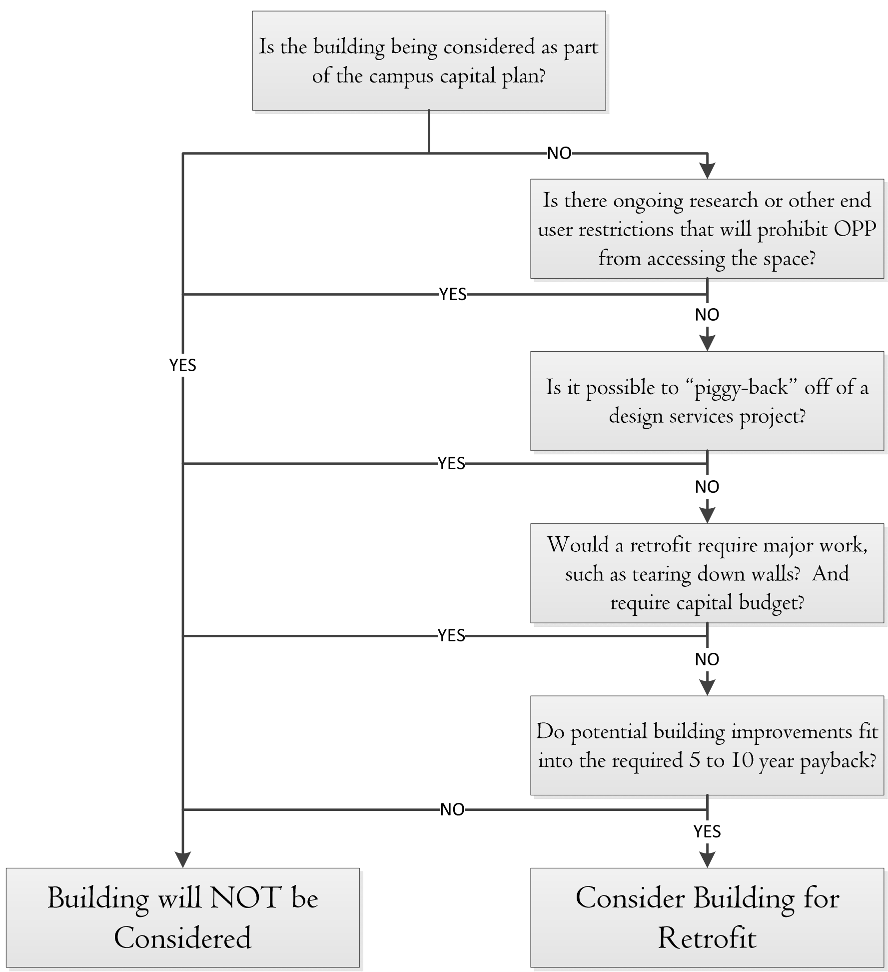



**Figure 2:** Decision Matrix

Figure 2 shows the decision matrix that was developed as a result of the semi-structured face-to-face interviews. As the matrix outlines, projects that are being considered as part of the campuses' capital plan will not be considered for an energy retrofit. Documenting this type of knowledge was helpful in understanding the challenges OPP's Energy and Engineering group may face during the initial project selection process. OPP Energy and Engineering group has the difficult challenge of evaluating the complex interactions of the various building systems and determining whether or not a retrofit makes sense from an economic stand point. Additionally, the energy group must also be careful to consider the impact any potential retrofit will have on building occupants and evaluate whether or not the upgrades could be part of a design services project; issues that your typical building owner do not have to consider.

## ENERGY PROJECT SELECTION PROCESS

Development of the decision matrix provided valuable insight into how Penn State selects projects for energy based retrofits. Examining Penn State's current process provided us with a clearer understanding of the OPP's current selection process while also adding some structure and formality to their energy auditing efforts. The practice of understanding Penn State's project selection process involved a series of face-to-face interviews with multiple individuals in the Energy and Engineering group. Focus groups were arranged following the face-to-face interviews as a means of validating the process maps that were developed as an outcome of the initial interviews.

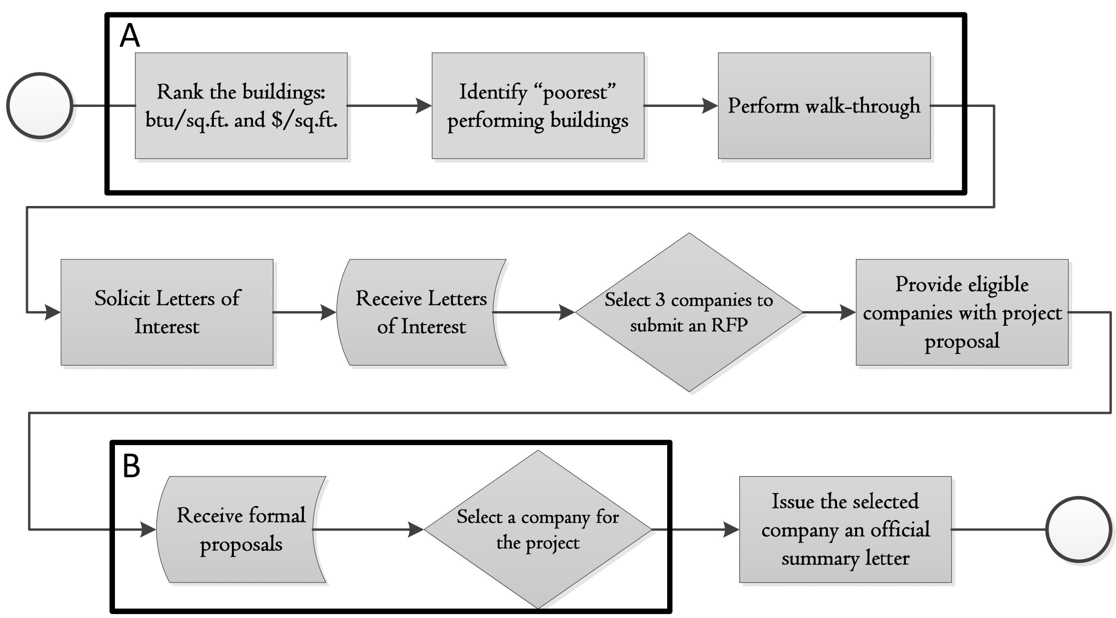



**Figure 3:** Penn State's Process for Selecting Energy Projects

Through the interviews regarding OPP's current selection process, data was collected to develop a process map which outlined the steps and the information which is needed at each step. Figure 3 shows the formal process that OPP's Energy and Engineering group follows for selecting facilities for energy based retrofit upgrades.

While working with the Energy and Engineering group, we witnessed their employees actually referring to this map as they were introducing outside industry members to OPP's project selection process.

Development of the process maps allowed for identification of issues with the current selection process. Within Figure 3 two separate portions of the process map have been outlined to indicate portions of the current process where the Energy and Engineering group has indicated the need for improvement. The outlined portion of the map marked with an "A" involves the initial steps taken to identify which buildings will be targeted for the energy projects. The Energy and Engineering group has indicated difficulties with these initial steps due to the lack of structure. The second outlined portion, marked with a "B", indicates when OPP receives the formal project proposals. The Energy and Engineering group members have described the difficulties they encounter when attempting to compare the proposals they receive. The assumptions made, upgrades investigated and purposed designs often vary substantially from one proposal to another. This makes it difficult for proposals to be compared and ultimately for OPP's Energy and Engineering group to select a company or even the appropriate project scope.

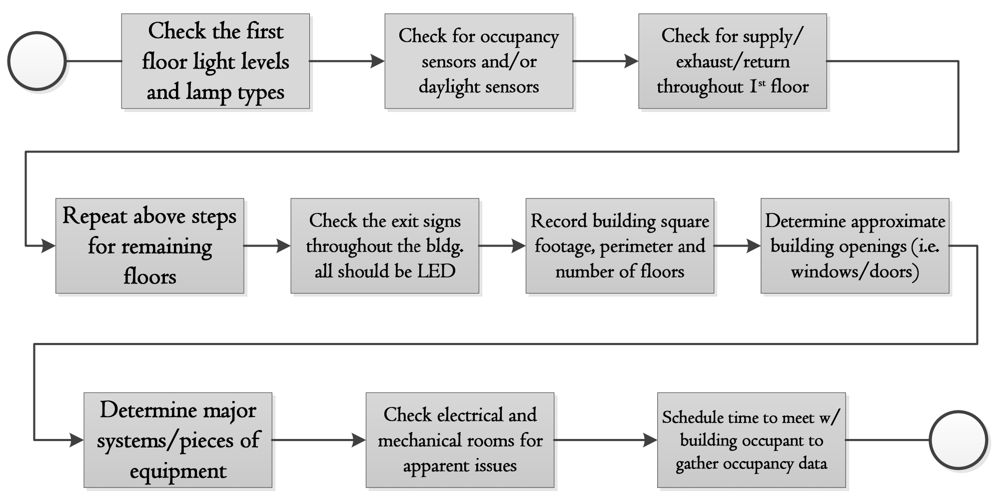


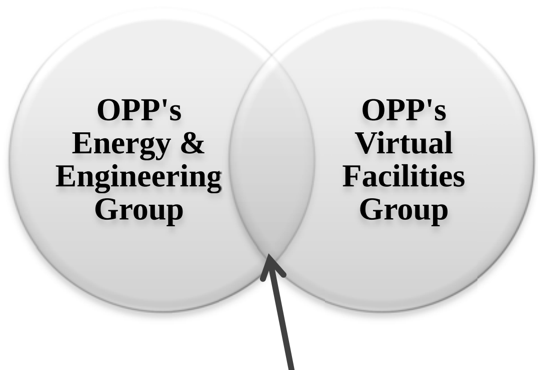

**Figure 4:** Penn State's Energy Auditing Walk-Through Process

The walk-through process is used to identify any obvious operation and maintenance issues (Deru, 2011). Information collected during the walk-through process is sometimes used to aid in the development of baseline energy models, so it is important the data collected is accurate. An accurate baseline model adds context to proposed retrofit upgrade designs (Crawley, 2008). To help address some of the challenges the Energy and Engineering group experiences when they are selecting projects to pursue, the walk-through process was shadowed and documented on several University Park projects. Once a process map which outlined OPP's walk-through process was developed, focus group discussions were held with the auditors to ensure the comprehensiveness of the map. OPP's walk-through process was also compared to a standard industry energy auditing walk-through process to ensure that the appropriate data was being collected. Documenting the walk-through process allowed them to formalize their process and ensure the appropriate information was collected. Figure 4 shows OPP's energy and engineering group's energy auditing walk-through process.

## INFORMATION REQUIREMENTS

Since Penn State performs continuous operation and maintenance on their buildings, along with upgrades, and multiple retrofits throughout the course of a buildings life time; they are ideal candidates to take advantage of Building Information Modeling (BIM). At the focus group discussions the Energy and Engineering group expressed interest in beginning to convert their energy information into a format compatible with OPP's BIM software. Hosting energy data in BIM related data structure would allow OPP's energy and engineering group to easily access the data for:

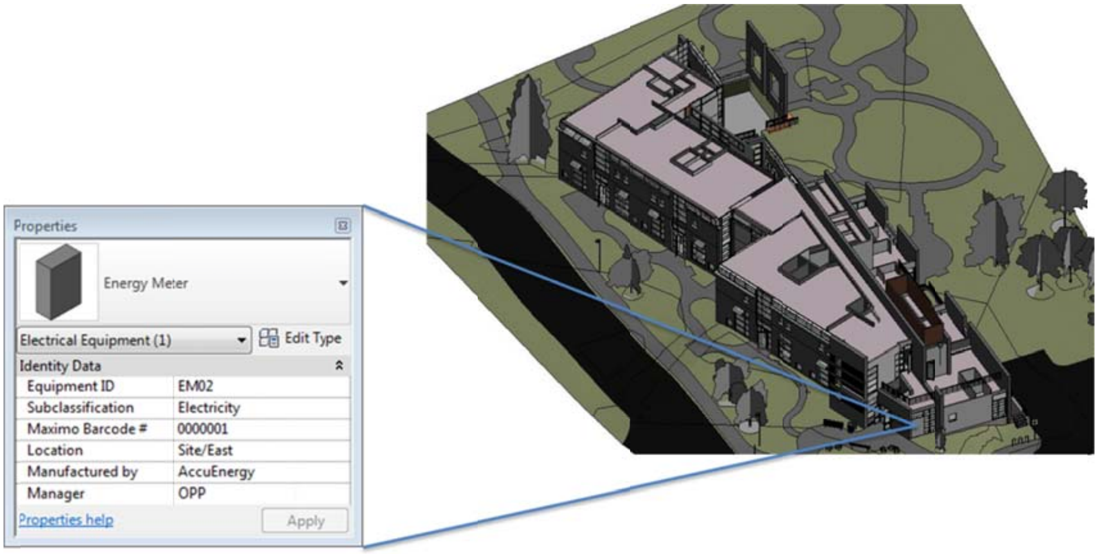
1. Performing routine operation and maintenance tasks
2. Track energy meters and other equipment, currently tracked manually
3. Access data needed to perform energy analysis and audits more efficiently




| | |
|---|---|
| **HVAC Equipment** | **Zones** |
| **Spatial Information** | **Pumps** |
| **Lamp Types** | **Equipment Motors** |
| **Thermostats** | **Heat Exchangers** |
| **Compressors** | **Access Panels** |

**Figure 5:** Data Overlap Between Energy & Engineering and Virtual Construction Group

Prior to this initiative, OPP's Virtual Facilities Group had a process in place to track maintainable facility equipment. Figure 5 shows some of the data overlaps between the Energy and Engineering group and the Virtual Facilities group. A series of focus groups were held with representatives from both the Virtual Facilities group and the Energy and Engineering group. At the meetings the Energy and Engineering group discussed what type of data that would like to track and along with useful data formats. The Virtual Facilities group members discussed the importance of obtaining user buy in and issues such as taking ownership of the data and frequency of updating the information. It was determined that if the data collected is not updated during facility operation, it will become obsolete within several years.




| | | |
|---|---|---|
| Energy Meters | Equipment ID | |
| | Subclassification (Select) | Electricity, Gas, Steam, Chilled Water |
| | Maximo Barcode # | # |
| | Location | Room # |
| | Manufacturer | |
| | Manager | Contractor or OPP |

**Figure 6:** Energy Meter Data Required by OPP (Dubler, 2012)

While the Energy and Engineering group expressed interest in tracking data, they seemed particularly interested in hosting energy metering data in the BIM database. Figure 6 shows how that energy meter data parameters would be stored and extracted from a Revit model, including an example of the energy attributes that will be collected from the design and construction teams on University projects. The energy meters were of particular interest because they are currently being tracked manually. They sometimes have difficulties locating the meters and have had challenges with tracking and monitoring each meter. Barcoding and monitoring the energy meters through BIM could help to streamline the process and alleviate some of the errors with the current metering efforts.

## RESEARCH SUMMARY

The Energy and Engineering group has already found value from the process maps developed in this research. They have been using the maps as references and guidelines for the processes they perform. Through standardizing OPP's energy auditing process, identifying the key information required to produce accurate energy audits, and establishing opportunities where the energy data can be tracked through BIM software PSU will be better positioned to achieve energy reduction goals. While it will take a period of time to integrate the energy information into OPP's BIM software, the OPP's Virtual Facilities and Energy and Engineering groups have established a working relationship and are well on their way to make this transition a success.

## FUTURE RESEARCH

Throughout this research, a notable problem which has been identified is the difficulty OPP has with comparing the proposal they receive for their energy based retrofit projects. When they receive the proposals, the analyses performed, energy simulation tools utilized and methodology for presenting the material varies vastly between reports. With this type of proposal variability, it can be difficult for OPP's Energy and Engineering group to compare proposals and select the best company for the project.

The Energy and Engineering group has expressed interest in standardizing the framework for their energy auditing reports. In standardizing this process, it is important that there remains a balance between standardizing the process and data enough to make it easier to compare reports, without limiting the design companies' ability to look at all the problems associated with the facility and all potential design solutions. This process will include standardizing the type of data and design assumptions required to be submitted without standardizing a specific energy modeling platform or design solutions.

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# STOCHASTIC ENERGY SIMULATION FOR RISK ANALYSIS OF ENERGY RETROFITS

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Abstract: Building energy modeling is a common procedure for the analysis of energy efficiency retrofits. Smaller retrofits of isolated systems, such as equipment motors and lighting systems, can often be made without the need for complete energy modeling; however, when the retrofit affects multiple systems, such as those involving the building envelope or the heating or cooling system, or when the retrofits of motors and lighting systems are so significant that they affect the heating and cooling load of the building, a more complete energy analysis is necessary. Because the exact inputs to building energy models are never known, and some inputs to the model are stochastic in nature (e.g., occupancy, plug-loads, lighting loads, weather), deterministic prediction of energy use is not only invariably inaccurate, it is actually inappropriate. When simple deterministic energy savings without uncertainty are used in economic analyses (e.g., return on investment), it is difficult to analyze the risk/benefit of the retrofit investment with true accuracy. A stochastic simulation, which includes the effects of input uncertainty and stochastic inputs, is a more appropriate way to predict the building energy use.

In this paper, we present a method for stochastic energy simulation that propagates probability characterizations of the input values through a computational engine to create probable energy use predictions. When this probable energy use is combined with forecasts of energy and construction costs, a probable estimate of return on energy efficiency measure investment is generated, and an economic risk/benefit analysis of the investment can be made. Such information is especially important to the growing energy service company market. The computational engine is based on the CEN/ISO monthly building energy calculation standards so its accuracy is well researched and validated, and the computational simplicity allows for efficient stochastic analysis.

**Keywords:** Stochastic, Uncertainty, Building Energy Analysis

## INTRODUCTION

As of 2011, residential buildings account for 22% and commercial buildings account for 19% of annual U.S. energy consumption (EIA 2011). Existing buildings make up the vast majority of the building stock with nearly 90% of the floor area of commercial and residential buildings having been constructed before the year 2000 (EIA 2003; EIA

2010), indicating there is a great need for energy efficiency retrofits. It is estimated that achievable energy efficiency measures could produce over $1.2 trillion in energy savings for a $520 billion investment by 2020 (McKinsey 2009); nevertheless, a variety of barriers impede the adoption of these measures by consumers, including investment of the time and resources required to conduct energy audits, create dynamic simulation models (Menassa 2011), and quantify energy efficiency performance risk and uncertainty (ZECBC 2011; Mills 2003).

Simplified energy modeling techniques that use reduced modeling input data are being developed to help overcome the time and resources barrier needed to perform the detailed audits required for dynamic simulation—and stochastic analysis is being introduced to provide the information needed for performing better risk and uncertainty analysis (Guzowski et al. 2012). The energy use probability estimates can be combined with construction cost probabilities and future energy cost probabilities to produce true probable return-on-investment (ROI) curves for a more complete analysis of energy efficiency retrofits as investments. In this paper we describe the application of stochastic methods to CEN-ISO monthly building energy models to account for input uncertainty in modeling and to produce estimates of probable building energy use and probable energy savings in a retrofit.

## METHODOLOGY

The basic premise of stochastic energy analysis is to consider many of the building and equipment parameters used in building energy models as uncertain quantities described by a probability distribution function (PDF). Some building inputs are inherently certain, such as the number of stories in the building; the basic type of heating, cooling, and air conditioning (HVAC) equipment; and the age of the building (even in cases where the exact age of a particular building might not be known, the approximate age is usually known with enough certainty that the input can be considered certain). Some inputs are fairly easy to estimate but are still subject to uncertainty (e.g., conditioned floor area, window area, wall area, window U value, and solar heat gain coefficient (SHGC) values), while others are difficult to estimate and can be highly uncertain (e.g., HVAC equipment and distribution system efficiencies, building air leakage rates). Still others are stochastic in their very nature and, hence, cannot be described accurately by a single number (e.g., occupancy, lighting power density, and equipment plugloads).

In stochastic analysis, the input parameter PDFs are propagated through the model to create an output PDF through standard Monte Carlo methods as shown schematically in Figure 1. A key to the use of Monte Carlo techniques is having an efficient computation model that accurately captures the basic building physics and accurately predicts energy consumption. For initial retrofit economic analysis, the model does not need to be capable of sizing equipment components or producing code-compliant output. Our method uses the CEN-ISO simple monthly model for predicting monthly and annual energy use in a number of end-use categories (ISO 2008). The basic CEN-ISO model is implemented in an Excel spreadsheet, whereas the Monte Carlo simulation is implemented in a MATLAB wrapper that computes the random input variables based on the assigned distributions, updates those values in the spreadsheet, reads back and stores the predicted energy use, and computes the output PDFs and associated cumulative distribution functions (CDFs).

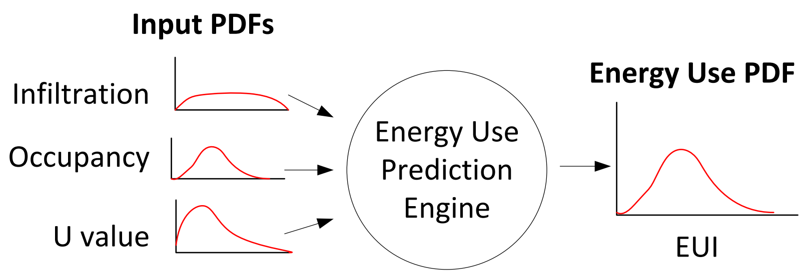


**Figure 1: Input PDFs are propagated through the energy model to produce a PDF for energy output.**

**Selection of Input PDFs**

One of the key aspects to gaining an accurate characterization of the predicted energy use is starting with accurate characterization of the inputs themselves, that is, having an understanding of the uncertainty associated with the various inputs. For each uncertain input, a PDF functional form and associated parameters must be selected based upon knowledge of the inputs.

In our implementation, we utilize uniform and beta distributions for PDFs, as shown in Figure 2. In the case of using inputs for which a range of values is known (i.e., a minimum and maximum possible value) but for which no more likely value can be assigned, a uniform distribution function is selected. When using inputs for which a range of values is known and a likely value can be estimated, a beta distribution is assigned. The use of a beta distribution avoids some of the statistical problems of truncated Gaussian or Poisson distributions (Gupta and Nadarajah 2004). Other researchers have effectively used triangle distributions instead of beta distributions (Heo et al. 2011).

Determining the range of possible values for each input parameter is an important step in the characterization of the inputs. In this study, a number of references were used to compile uncertainty data, which, in turn, were used to determine the possible range of parameters. Uncertainty information used to determine the ranges of expected values were obtained from a variety of sources, including Hill et al. (2008), Macdonald (2002), Dunn (2005), Tamura and Shaw (1976), Emmerich et al. (2005), Persily and Gorfain (2004), and ASHRAE (2009, 2010, 2011a).

When an input value is not collected during an audit, a normative input value can is assigned based upon information gathered from other inputs, including the basic building type, the year built, basic HVAC type (system type, fuel type, etc.). If the additional information can suggest a most likely value, a beta distribution is assigned with maximum and minimum values derived from the sources above; but if not, a uniform distribution is assigned with maximum and minimum values derived from the sources above.

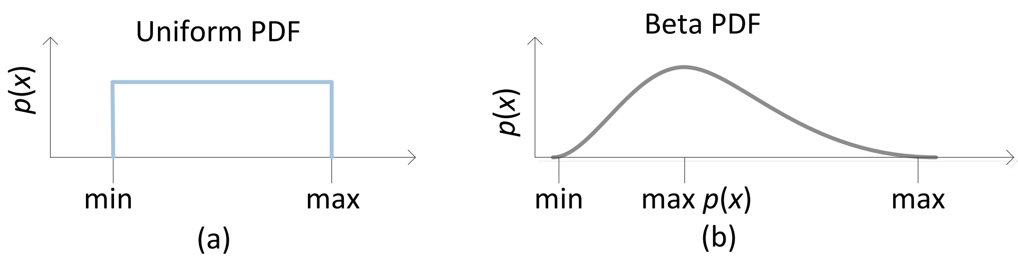


**Figure 2: Shapes of the (a) uniform and (b) beta Probability Density Functions (PDFs).**

As an example, consider assigning a distribution to gas boiler efficiency. The efficiency of the actual gas boiler ranges from 0.6 to 0.95 depending upon the age, type, and condition of operation. If nothing is known about the hot water boiler other than the fuel type and that the building was built around 1970, a beta distribution with a range of 0.6 to 0.95 and a peak at 0.7 would be assigned for the following reason: it is most likely that a building built in 1970 will still be using the original boiler with an efficiency of about 0.70, although there is a small possibility that a boiler retrofit with a higher-efficiency unit has already taken place *or* that the boiler actually has a lower operating efficiency. If it is known that a boiler retrofit did not take place, then the range might be reduced to 0.6 to 0.8.

Note that although weather is a highly stochastic and uncertain quantity, uncertainty in the weather data is not considered in the implementation presented here. For a more complete uncertainty analysis, especially for investment risk assessment, the stochastic nature of weather could be included. When comparing the predictions of the model to measured data, such as in a retrofit scenario, actual meteorological year (AMY) data obtained from a nearby weather station should be used instead of typical meteorological year (TMY) data, and in that case, only the uncertainty of the weather instrumentation itself should be considered (i.e., not the stochastic variability of the weather).

**Monte Carlo Algorithm**

Once all fixed input values are known and input PDFs have been assigned to uncertain inputs, the basic Monte Carlo method is implemented as follows, as shown in Figure 3 (a). Note that this algorithm runs for a fixed number of Monte Carlo runs as opposed to checking for convergence of PDFs of the selected output values; the approach is used because the model runs so fast that it is easier to compute additional Monte Carlo runs than are necessary for convergence than to actually test for convergence.

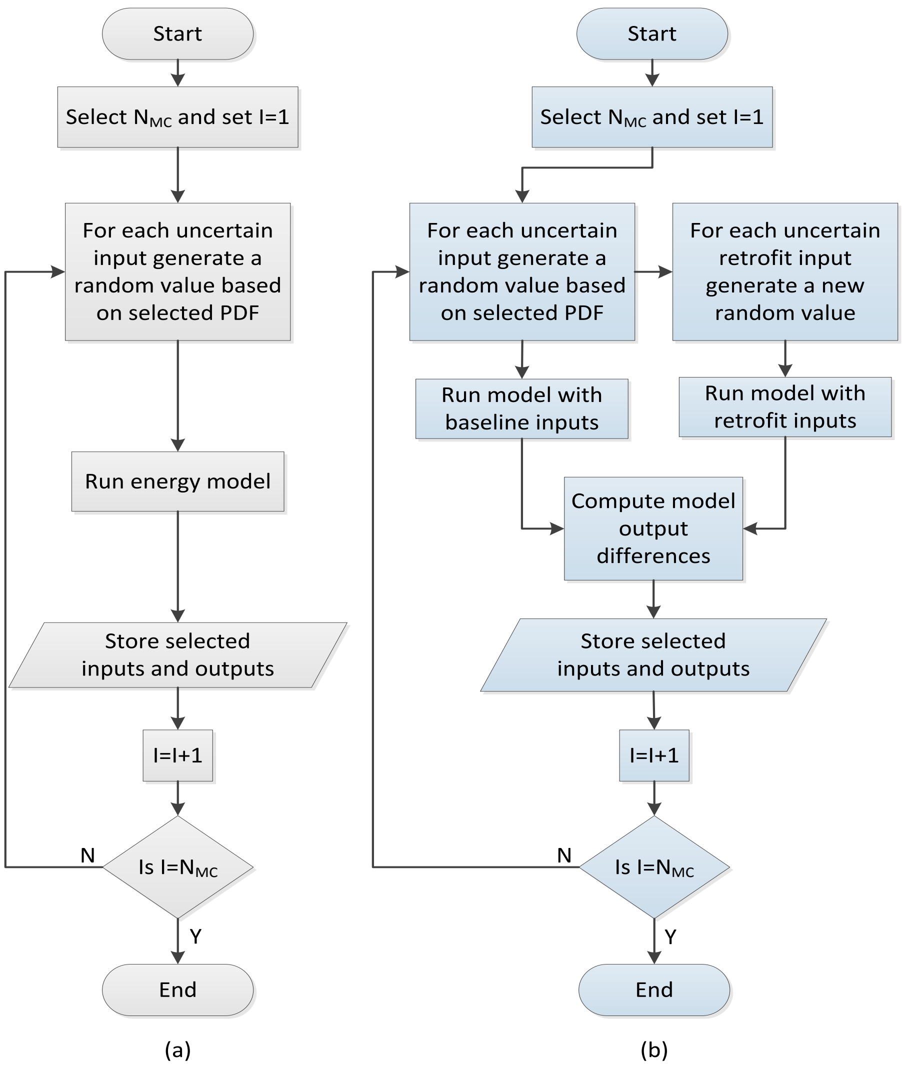


**Figure 3: Basic Monte Carlo energy computation algorithm for (a) energy use intensity (EUI) calculation and (b) retrofit energy savings.**

When using the Monte Carlo method for the computation of energy savings from a building retrofit or for a design variation, analysts must be careful in the calculation of energy savings. One cannot simply compute the energy use PDFs for the baseline and modified cases and subtract them as independent random variables because the two energy use PDFs are highly correlated. The correct way to compute energy savings involves subtraction of the baseline and modified case for each Monte Carlo run, as shown in Figure 3 (b). In computing the modified case, exactly the same input values should be used as the baseline case except for those inputs that are modified as part of the retrofit/design change.

In most cases, the PDFs of the selected outputs can be adequately estimated through the computation of a scaled histogram, and then the CDF can be adequately estimated using the running cumulative sum of the scaled histogram. For a smoother and more statistically robust estimate of the PDF and CDF, we have implemented the nonparametric kernel density estimation as developed by Botev et al. (2010).

## APPLICATION

As an example of using the method, let us compare the predicted savings for the chiller retrofit of an existing building with two different levels of audit fidelity for the input parameters. The high-fidelity audit is a very detailed audit where most of the input parameter values have been highly accurately measured or estimated. This type could correspond to an ASHRAE Level 2 or Level 3 audit (ASHRAE 2011b). The low-fidelity audit is a very “gross” audit, where very little information is available, and most input parameters must be assigned as normative values estimated from the basic available information. This audit level corresponds to one that is even less detailed than an ASHRAE Level 1 audit. Analysts often appreciate having even rough estimates of energy savings deriving from a retrofit to help them determine whether a more complete (and expensive) audit should even be performed on the building; thus, the ability to predict savings and understand the uncertainty of those predictions with a low-fidelity audit is important. The use of stochastic energy analysis can be very useful in this first step because confidence bounds can be placed on the energy savings predictions.

In our example case, the building itself is a 32-story high-rise with a conditioned floor area of 76,600 $m^2$. It has a stone-and-glass panel curtain wall with a nominal opaque wall U value of about 0.35 $W/K/m^2$ and window U value of about 3.2 $W/K/m^2$, a window SHGC of about 0.5, and a window/wall ratio of about 50%. (Unfortunately, a detailed list of the input parameters and uncertainty assignments for the low- and high-fidelity models is too large to present in this paper.) In the application, 10,000 Monte Carlo runs were chosen by noticing that convergence was obtained with 2,000–5,000 runs through trial and error and then selecting a much larger number to ensure convergence. Actual energy use in the building was obtained from monthly utility bills.

### Annual EUI Prediction

The stochastically computed PDFs and CDFs for the annual energy use intensity (EUI) for both the low- and high-fidelity audits of the facility are shown in Figure 4, along with the measured energy use for the building. There were 10,000 Monte Carlo runs for this computation. The utility of the stochastic predictions can be seen through interpretation of these plots. The PDF plots can be used to quickly assess not only the expected EUI but also range of uncertainty of the predictions. The peak of the PDF plot is the value that occurred most often in the Monte Carlo simulations (i.e., is the mode of the Monte Carlo

EUI predictions). The overall width of the PDF curve is a visual indication of the range of uncertainty. The CDF plot can be used for a more quantitative analysis of the uncertainty in the prediction. The EUI at which the CDF equals 0.5 is the value at which there is equal probability of the EUI being a higher or lower value (i.e., is the median EUI). The confidence bounds on the prediction can also be obtained directly from the CDF. For example, the 5% and 95% confidence bounds are obtained from finding values of EUI where the CDF=0.05 and CDF=0.95.

In Figure 4, we can see that peak of the PDF and the CDF=0.5 both occur at an EUI of about 155 kWh/m$^2$/yr for the low-fidelity model and of about 136 kWh/m$^2$/yr for the high-fidelity model. The large uncertainty in the prediction of the low-fidelity model is evident in the large width of the low-fidelity PDF. From the CDFs, we can see that the low-fidelity model has 5% and 95% confidence bounds of 115 kWh/m$^2$/yr and 190 kWh/m$^2$/yr, respectively, whereas the high-fidelity model has 5% and 95% confidence bounds of 115 kWh/m$^2$/yr and 154 kWh/m$^2$/yr, respectively.

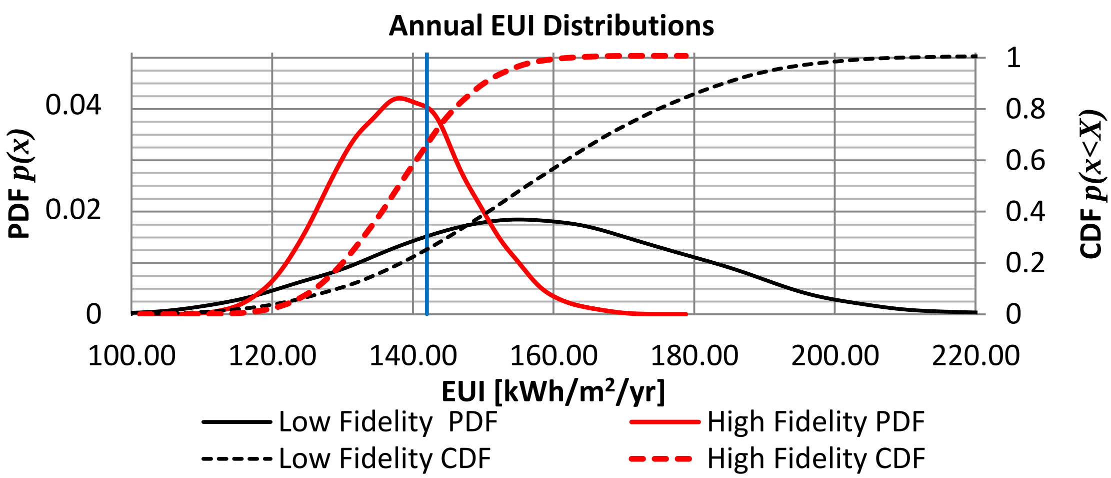


**Figure 4: Annual EUI PDFs for Level 1 accuracy and Level 2 accuracy with 10,000 Monte Carlo runs. The vertical blue bar is the actual measured energy use for the building.**

The CDF can be quite useful for energy estimation in early design phases where little information about the proposed design has been developed but performance goals have been set. During the initial design phases of highly energy efficient buildings, analysts could use the CDF to estimate whether the proposed design meets or exceeds a target EUI with a given level of confidence. Looking at the low-fidelity CDF in Figure 4, for example, we can see that there is a 90% chance that the EUI is less than 185 kWh/m$^2$/yr, a 50% chance that the EUI is less than 155 kWh/m$^2$/yr, and a 10% chance that the EUI is less than 130 kWh/m$^2$/yr.

In Figure 5, we see a plot of the monthly EUI values with the 5% and 95% certainty bounds for both the low- and high-fidelity audit cases along with the measured data. What can be clearly seen in Figure 5 is the reduced uncertainty in the monthly predictions using the high-fidelity audit data, but even with the low-fidelity data, the measured energy use is within the 5% and 95% confidence bounds for each month.

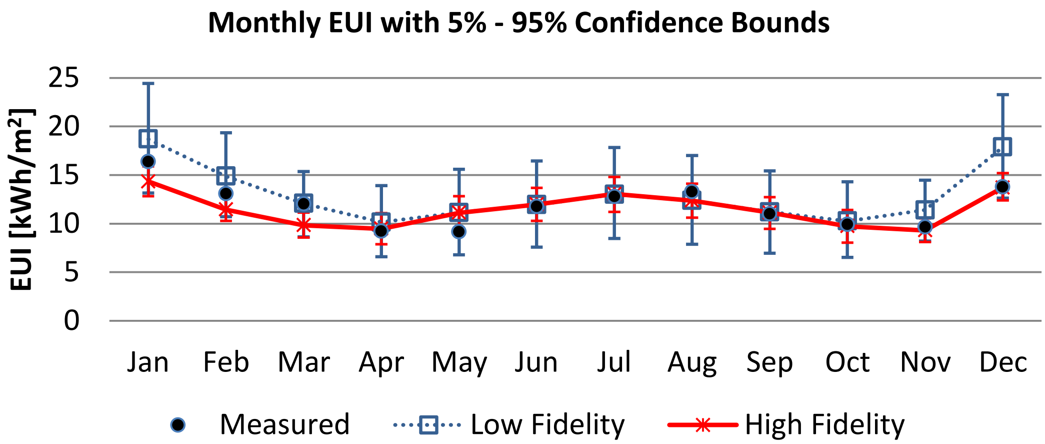


**Figure 5: Monthly EUI predictions with low-fidelity audit data, high-fidelity audit data, and also a plot of the measured data. The low- and high-fidelity data points are the median EUI, and the error bars represent the 5% and 95% confidence bounds for the prediction.**

**Retrofit Energy Savings Predictions**

One of the most important uses of the stochastic energy estimation is to provide probable energy savings for a retrofit. To show an example of this, consider a retrofit of the same building with a set of new high-efficiency chillers. In the baseline building, the chiller coefficient of performance (COP) is modeled as a uniform distribution between 3 and 6 and the mean partial load value (mPLV) is modeled as a uniform distribution between 0.5 and 1.0. In the retrofit building, the chiller COP is modeled as a beta distribution between 7.0 and 8.0 with a peak of 7.6, and the mPLV is modeled as a beta distribution between 1.1 and 1.3 with a peak at 1.2. The stochastic predictions again used 10,000 Monte Carlo runs, and the resulting energy savings PDF and CDF are shown in Figure 6.

From Figure 6, we see that the savings PDF are skewed toward the lower savings value, which means we have higher uncertainty in the upper bound of energy savings than in the lower bound. The mode of the low-fidelity audit prediction is about 9.0 kWh/m$^2$/yr in savings, while the median is about 12.0 kWh/m$^2$/yr and the 5% and 95% confidence bounds are 5 kWh/m$^2$/yr and 30 kWh/m$^2$/yr, respectively. The mode of the high-fidelity audit prediction is about 12.2, while the median is about 13.5 kWh/m$^2$/yr and the 5% and 95% confidence bounds are 8.5 kWh/m$^2$/yr and 18.5 kWh/m$^2$/yr, respectively. Perhaps more importantly, the low-fidelity model predicts that the energy savings will be at least 6 kWh/m$^2$/yr with 90% certainty, and the high-fidelity model predicts the energy savings will be at least 10 kWh/m$^2$/yr with 90% certainty. This information can be used to quickly determine the viability of a retrofit, sort between retrofit options, and determine the need for a more complete building audit.

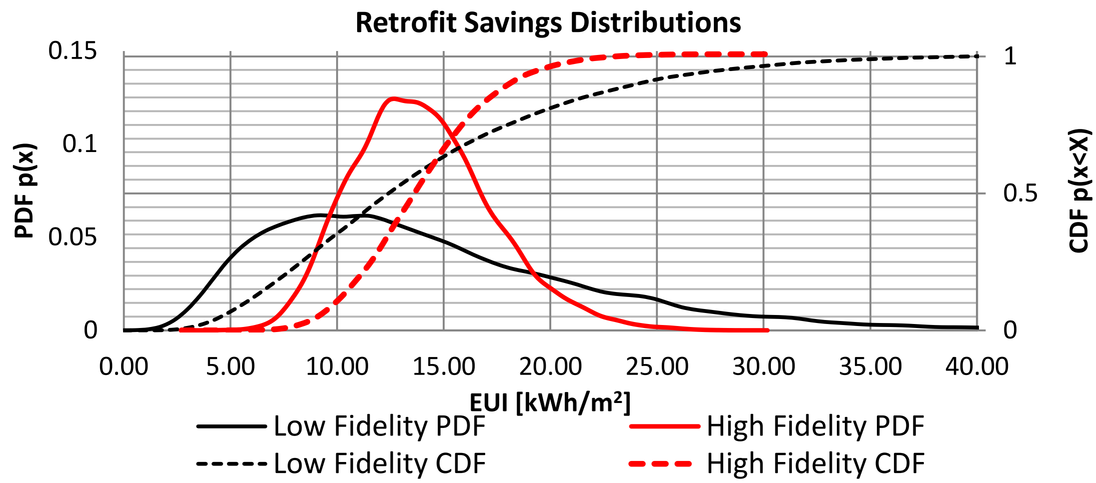


**Figure 6: PDF and CDF plot for of the predicted energy savings of a chiller retrofit.**

## CONCLUSIONS

This paper discussed and demonstrated the use of Monte Carlo methods for the stochastic prediction of probable energy use. After presenting the basic algorithm for generating probability density functions (PDFs) and cumulative density functions (CDFs) for both energy consumption and retrofit energy savings, an example application of the method was presented, and interpretation of the resulting PDFs and CDFs was discussed, with the intent that implementing a stochastic assessment could help building engineers and analysts use limited resources most effectively when weighing energy use decisions.

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# TOWARDS AN INTEGRATED PROCESS MODEL AND DECISION SUPPORT SYSTEM FOR HIGH PERFORMANCE GREEN RETROFITS

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**Abstract.** *There is widespread recognition of the importance of the built environment in tackling the current energy and sustainability challenges. It is well known that with existing buildings constituting more than 98% of the building stock, the greatest impact on reducing building energy consumption in the US will result from retrofitting existing buildings. These need to be based on radically improving their energy efficiency and overall performance. The aim of the project, on which this paper is based, is to develop an integrated process model and decision support system (DSS) that can provide proactive guidance to facility owners/managers in undertaking high performance green retrofits of existing buildings. This is being addressed through detailed case studies of a number of high performance green retrofit projects, the modeling of the retrofitting process, the identification of key decision criteria, and the development of an appropriate decision support system (DSS). The DSS will provide guidance on technical alternatives available at each decision point along the retrofitting process, including the link to associated energy performance outcomes and cost implications. The paper presents the approach being adopted in the development of a process model for energy efficient retrofits, and an intelligent DSS that enables informed choices to be made.*

*Keywords: Energy Efficiency, Retrofits, Integrated Process Models, Decision Support Systems*

## 1. Background

There is widespread recognition of the importance of the built environment in tackling the current energy and sustainability challenges that threatens the survival of future generations. Given that buildings account for more than 40% of the energy consumption in the United States, it is vital that minimizing energy utilization and finding alternative energy sources for buildings should be a top national priority. This is now being recognized by the federal government and there is significant interest in buildings that not only have net-zero energy utilization but could actually be net generators of energy. Improving the performance of commercial and residential buildings has been identified by both the current U.S. administration and the World Sustainable Business Council as essential in: radically reducing the carbon footprint of buildings; ensuring the energy security and independence of a sovereign nation; reducing significant health risks linked to indoor air quality and lighting environments; and providing buildings that are structurally robust. However, much research needs to be done to develop the necessary technologies, tools, systems, components, materials, and methods that will make this an economic reality.

The nation's 107 million households and more than 4.9 million commercial buildings consume more energy than the transportation or other industry sectors, accounting for nearly 40 percent of total U.S. energy use. The total utility bill for energy used by U.S. buildings topped $369 billion in 2005. Building energy services — lighting, warmth in the winter, cooling in the summer, ventilation, air cleaning, humidity control, water heating, electronic entertainment, computing, refrigeration, and cooking — require significant energy use, about 40 quadrillion Btu (quads) per year (2008). Policies, regulations, and incentives are now being implemented in the public and private sectors to reduce building energy consumption by 30 – 50% by 2020, to achieve a concept known as "net-zero energy" by 2025, and to achieve a 42% reduction of $CO_2$ environmental concentrations (i.e., "carbon footprint") by 2030.

It is well known that with existing building constituting more than 98% of the building stock, the greatest impact on reducing building energy consumption in the US will result from retrofitting of existing buildings. These need to be based on radically improving their energy efficiency and overall performance. Facility owners/managers are now exploring ways to cost-effectively do this across their set of building assets. However, very little guidance exists on how best to do this.

### 1.1. Limitations in Current Approaches

Deep retrofit projects consist of multidisciplinary decisions from the lens of green building and retrofitting characteristics. These decisions require integration of all key stakeholders early in the process. However, this early collaboration is limited through certain contractual arrangements or the time constraints of individual contributors. Even if a collaborative working process has been established, the complexity of decision making process should be clearly defined for the sake of targeted building performance. Since the collaboration is seen as key of these complex processes, we are focusing on the attributes of an integrated decision making process for deep retrofit projects to provide guidance on technical alternatives available at each decision point along the retrofitting process, including the link to associated energy performance outcomes and cost implications. The need for an early prediction of building energy performance leads this study to search for optimum decision sets that achieve certain energy efficiency targets. The study presents the approach being adopted in the development of a process model for energy efficient retrofits, and an intelligent DSS that enables informed choices to be made.

## 1.2. Research Aim and Objectives

The aim of this project is to develop an integrated process model and decision support system that can provide proactive guidance to facility owners/managers in undertaking net-zero energy retrofits of existing buildings. The specific project objectives include (Figure 1):

1. To investigate and characterize the decision variables involved in the retrofitting of existing buildings;
2. To identify the critical technical criteria and opportunities for migrating an existing building to high performance energy status;
3. To undertake case studies of building retrofit projects to gain first-hand experience of the current approaches being adopted and to understand the practical context for decision making;
4. To develop and validate a detailed process model that documents the most appropriate approach to follow in undertaking high performance energy retrofits – this will incorporate key technical decision points;
5. To develop and evaluate a decision support system that provides proactive technical support to facility owners/managers in choosing the most appropriate options at key stages of the building retrofitting process;
6. To formulate guidelines for high performance energy retrofits.

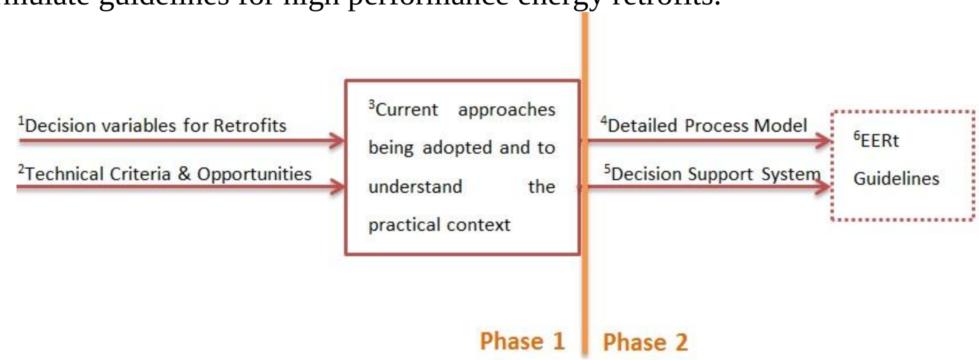


Figure 1: Research methodology steps

### 1.2.1. Scope

In order to measure the impact of integration on project success, Pocock and Liu introduced a quantifiable approximation of integration as degree of interaction. This approximation is based on a formula which includes indicators such as the number of people interacting and the duration of the interaction. It is hard to degrade the process from quantity and quality of time, people, and methods to number of interaction and people. This study also assigns different weights to different phases which helps quantify the effect of decisions taken early in the delivery process. Planning, schematics, design development, and procurement phases are the most crucial phases since 91% of the performance-related decisions are taken during these processes (Pocock 1996).

In most cases, the earlier the decision to improve the energy efficiency is made, the better the end building performance will be. The actual design phase is becoming the ground for enabling these roles, decisions, and time. We will be focusing on the integrated design phase since planning, schematics, design development, and procurement phases are the most crucial phases.

The crucial period of the integrated project delivery is the actual design process. This is where all team participants meet and provide their expectations, insights, and expertise for a variety of decision options.

Regardless of how the parties decide to structure the decision making body, in an integrated project one overriding principle directs the decision making body: all decisions are made in the best interests of the project (AIA, 2009). In such a collaborative and flexible working environment, distribution of responsibilities is the key for the execution of services while working towards a common goal. While everyone is working towards a defined and common goal, they should know their shared responsibility.

Even though responsibility is shared collaboratively through the decision making process, there are certain authorities taking the certain decisions as well as the responsibility. In general, an umbrella entity approves the final decision while the integrated design teams generate and present design decision options to this entity. In the meanwhile, an integrated project team works on improving the potential of design options collaborating with related consultants. These teams have representatives to present the different party's contribution to the decision during the collaboration process. In the observed processes, there are overlapping members from related parties to carry the responsibility of the design decision throughout the delivery process.

## 2. Energy Efficiency in Building Retrofits

It is well known that with existing buildings constituting more than 98% of the building stock, the greatest impact on reducing building energy consumption in the US will result from retrofitting existing buildings. These need to be based on radically improving their energy efficiency and overall performance. The retrofitting process consists of improving the building with new energy systems and comfort levels according to the targeted savings and adapted space requirements in the framework of reducing the energy consumption and using the generated energy in an efficient way.

Eighty percent of the current commercial building area will be operational in 2030 (RMI, 2012). The Rocky Mountain Institute (RMI) estimates that $1.4 trillion dollar value stands to be gained over the next 40 years from intervening with deep energy retrofits using whole systems design.

There are many ways re-use a building by following different processes according to need and condition of old building. In order to clarify the distinction of these processes, Johnson and Wilson (1982) defined various terminologies used in renovation and restoration of buildings in upgrading of facilities. Then, Rosenfeld and Shohet (1999) improved the terminology by increasing the resolution through the lens of *maintenance and repairs* to keep the facilities operable (Figure 2). In addition to scheme below, Kashyap (2007) tried to located refurbishment towards the end of a property's life cycle and typically follows a series of increasing expenditure in the form of maintenance, repairs, restoration and replacements.

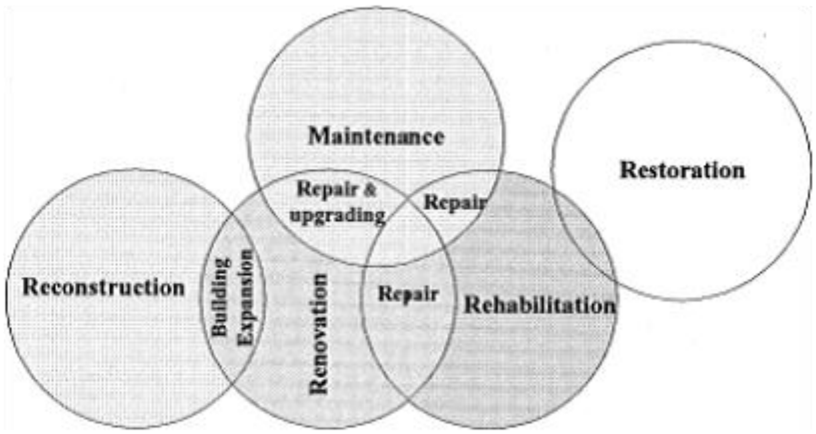


Figure 2: Terminologies for upgrading of constructed facilities Source (Rosenfeld and Shohet, 1999)

*A renovation* is generally performed due to the need to meet the special requirements of an owner. It can include envelope and structural upgrades as well as the special layout changes. However, *retrofit* process requires improvement on building's energy performance including mechanical, electrical, and plumbing design as well as insulation opportunities. The major difference between renovation and retrofit rely on where renovation is undertaken with an ambient sensitivity of that primarily benefitted the owner, retrofitting undertaken for energy sensitivity benefits not only the owner, but more so the environment and the community because it helps to decrease the collective demand for scarce energy resources. *Deep retrofits* achieve bigger energy savings and other benefits at equal or lower cost, driving much larger savings (more than 50%) than traditional retrofits (RMI,2012).

## 3. Research Methodology

The review of related work is limited, since the retrofitting experiences in the level of high performance energy efficient deliveries are currently evolving in regards to new technologies and processes followed. Rocky Mountain Institute delivered a compressive study on differentiating activities required for delivering deep retrofit projects. This study is utilized to establish the boundaries of design process understanding regarding design activity sequences. Incorporating energy efficiency related decisions into design at earlier phases is crucial. Hence, we converted the recommendations that are stated by RMI into a process map. "Launch" phase is the earliest phase of a proposed design process (Figure 3). It has unique steps as setting measurable goal for energy reduction performance, gathering data from previous utility bills, audit results, etc., and calibrated energy model with inherent building conditions to develop a baseline prior to start design.

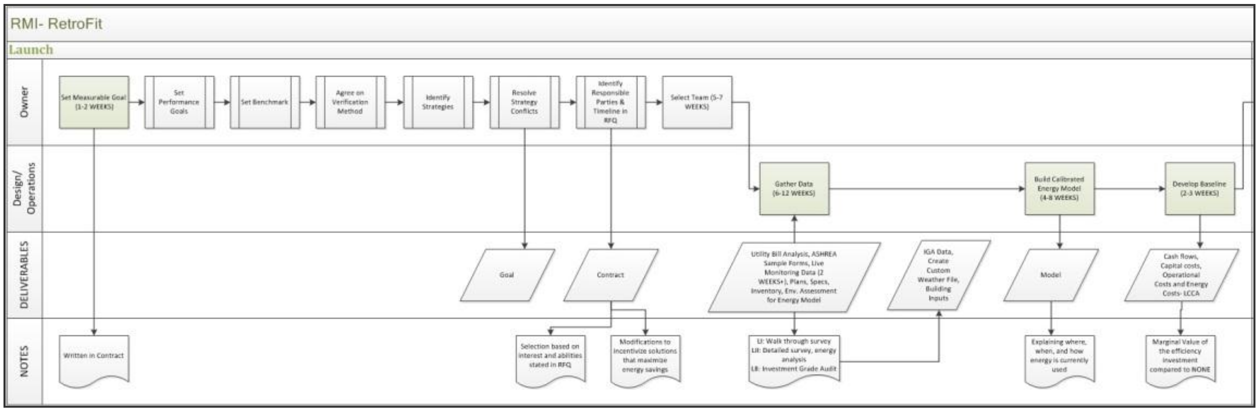


Figure 3: Launch phase recommended actions adapted from RMI, 2012

## 3.1. Case Studies

Empirical Inquiry that investigates a contemporary phenomenon within its real life context; when the boundaries between phenomenon and context are not clearly evident; and in which sources of evidence are used (Yin, 1984). In this project, case study has been found appropriate to gain first-hand experience of the current approaches being adopted and to understand the practical context for decision making in retrofit process.

We observed two case studies in Pennsylvania. Both of the projects are superior examples in terms of the collaborative design process and new technologies used. The decision making process is transparent due to the aim of delivering showcase in regards to energy efficient technologies and techniques used as well as the process followed.

### 3.1.1. Connelly School Retrofit Project, Pittsburgh, PA

Connelly School retrofit project (300,000sqf) is a green technology demonstration showcase building under the ownership of Pittsburgh Green Innovators Inc. This deep retrofit project achieves almost 49% reduction in energy consumption of the building through the integrated mechanical, electrical and plumbing (MEP) system design decisions. Decision making environment was collaborative due to the design-build delivery type selection. Based on the interview conducted to mechanical designer of the project, the general process characteristics are mapped out as below (Figure 4):

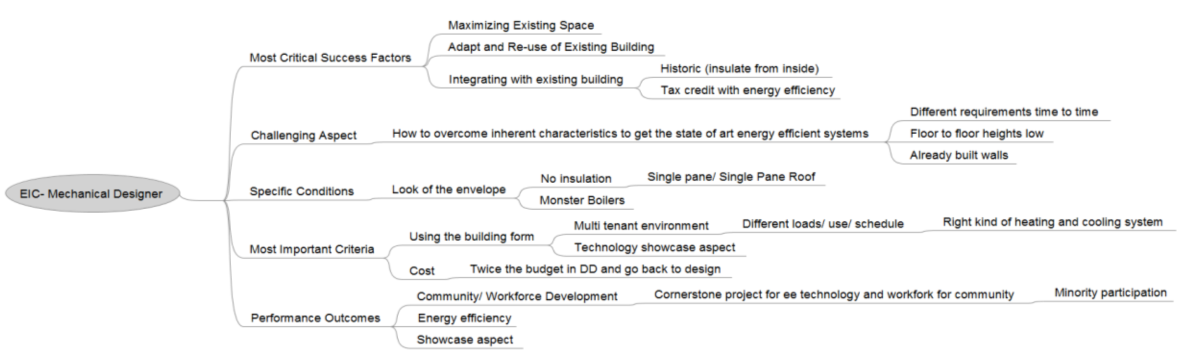


Figure 4: EIC, Mechanical Designer general condition interview content

The MEP design of the newly named Energy Innovation Center (EIC) had targeted a state-of-the-art, historically sensitive, energy efficient design. Energy optimization of the project is expected to achieve 49% compared ASHRAE 90.1-2007 and achieve all 21 points under LEED Core and Shell EA credit 1.the role of the MEP systems within the Energy Innovation Center, in addition to the more common aspects, will be to showcase energy innovative technologies, to provide demonstration and training of sustainable building systems, and to provide flexibility for future energy efficient technologies. The MEP concepts for the Energy Innovation Center have been developed to meet the goals of the project while maintaining the historical aspects of the former Connelly Trade School. The building typology is in two forms and functions; saw-tooth roofed section serves as a light industrial/manufacturing function and the tower portion serves for certain tenants related to green technology suppliers with training purposes. These two sections will be equipped with different technologies in order to observe the performing levels for learning purposes (Figure 5)

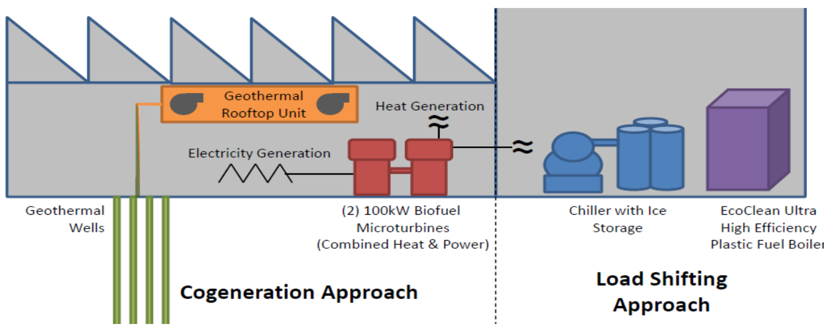


Figure 5: Energy generation technologies at EIC

Energy efficient aspects of the project include natural light and day lighting controls, insulation of the existing building envelope, replacement of existing curtain wall window systems, a super-critical carbon dioxide-based geothermal ground source heat pump system, active chilled beams and radiant panels, Dedicated Outdoor Air Systems (DOAS) with MERV-13 filters, passive desiccant wheels for moisture control, energy recovery and Demand Controlled Ventilation (DCV). The building systems will also be designed to demonstrate demand side energy management control strategies through the use of ice storage, and the future implementation of a Combined Heat and Power (CHP) system with an absorption chiller that utilizes waste heat from the CHP plant. The proposed systems are *energy efficient, provide superior in indoor air quality, reduce the amount of mechanical space, minimize the historic impact to the exterior and maximize the use of rentable floor space.* These are the general decision making criteria that shaped the final MEP system selection within the observable mechanical room (Figure 6); and through the building with smaller ducts and shorter pipes.

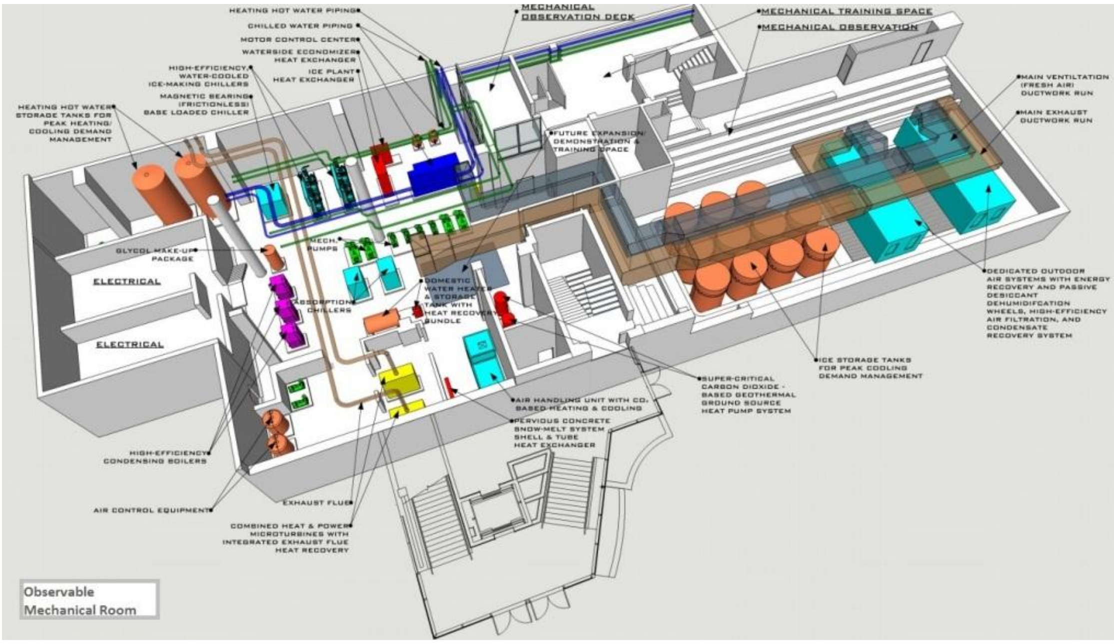

Figure 6: Observable mechanical room drawing

Tenants will be provided with advanced thermal comfort through dehumidified outdoor air and local sensible cooling. This approach saves energy by providing lower space relative humidity levels and warmer space temperatures to achieve the same level of comfort. Tenants will also have the opportunity to utilize numerous sensible cooling technologies within their space such as chilled beams, radiant cooling panels, or conventional fan coils and/or terminal heat pumps. However, these MEP design selections (Table 1) will be applied in three phases due to flexibility of tenant load capacity and future donation availability.

Table 1: MEP design selections by phases

| | Phase #1 | Phase #2 | Phase #3 |
|---|---|---|---|
| Pervious Parking Lots | √ | | |
| Green Roofing | √ | | |
| Exterior Sun Shades | √ | | |
| Day Lighting | √ | | |
| Insulate Interior Walls | √ | | |
| Insulate Roof | √ | | |
| Operable Windows | √ | | |
| Storm Water Collection System | | √ | |
| Geothermal Wells | √ | | |
| Hot Water Solar Heating | | √ | |
| Desiccant Dehumidification | | √ | |
| Demand Controlled Ventilation | | √ | |
| Boiler Exhaust Heat Recovery | √ | | |
| Inter-season Heat Transfer Storage | | | √ |
| Wind Turbines | | √ | |
| Photovoltaic Roof Panels | √ | | |
| Energy Efficient Lighting | √ | | |
| Water Valve Controls | √ | | |
| Demand Side Management | √ | | |
| Energy Usage Monitoring | √ | | |
| Ice Chiller | | | √ |
| Biomass Fuel System | | | √ |

### 3.1.2. Building 661 Retrofit Project in Navy Yard, Philadelphia, PA

The Building 661 is newly named Energy Efficient Buildings (EEB) Hub will be nearly 30,000 sqf research laboratory and education facility. It is established in Philadelphia by the U.S. Department of Energy (DOE) as an Energy-Regional Innovation Cluster (E-RIC) on February 1, 2011 with a unique dual mission of improving energy efficiency in buildings—literally re-energizing them for the future—and promoting regional economic growth and job creation from our headquarters in Philadelphia's Navy Yard (2012). Even though the delivery type is defined as Design-Bid- Build, the project team is working on an integrated design process non-contractually. The design priorities had been set collaboratively during a workshop as:

- Energy Efficient
- Daylighting (Figure 7)
- Integration w/ outdoors/environment/woods: visual and physical
- Aesthetics: Building as a Gateway; “sustainable aesthetics” fitting PSU image
- Sensory-rich, stimulating and scale appropriate environment
- Safety and Security
- Clear commissioning requirements
- Healing the site; restorative/regenerative; co-evolutionary managing of site
- On budget
- Natural Ventilation and Lighting, with User-interaction
- LEED certification, at the highest-level attainable by budget

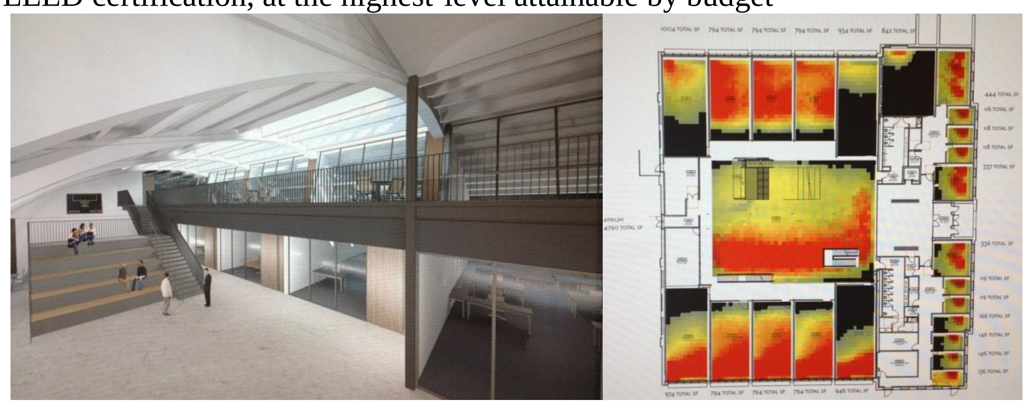

Figure 7: Daylighting analysis

The reduction in energy consumption is targeted as 50% to deliver a deep retrofit showcase with a LEED Platinum certification level. Due to the nature of integrated design process, all design decision are taken in a collaborative environment with Penn State representatives (owner and tenants), architects, contractors, and specialty consultants for MEP design considerations. The unique feature of this project is the early engagement of all project team regularly and frequently. The Figure 8 is showing the meeting frequency of the team with certain focus teams and different responsibility agendas. These meeting points are representing the decision making stages via information exchanges through the specific project stage.

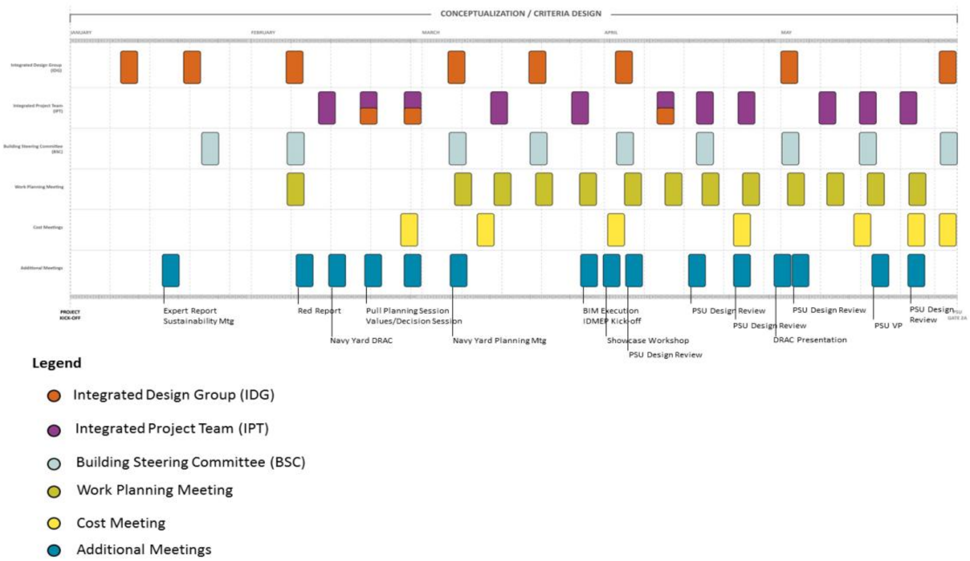


Figure 8: Decision making stages during criteria phase of EEB Hub project

An informal integrated project delivery required everybody bringing together at the project initiation phase in order to select *right consultants, establishing budget, schedule, and communications* collaboratively which is stated in the interview with the project manager shown as below (Figure 9). What we mapped in here is what the critical decisions are, how-why these decisions are taken in contract to other options at what time, and by whom from the project management stand point in the project initiation phase.

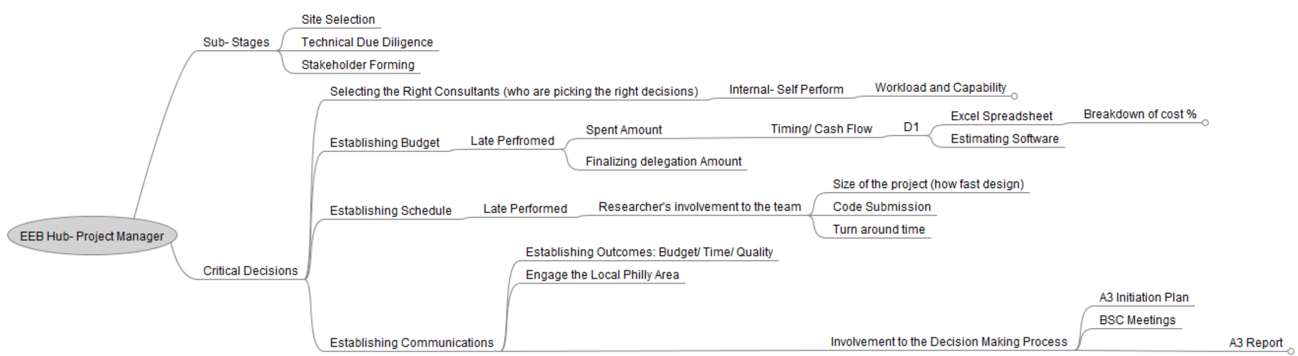


Figure 9: EEB Hub, Project Manager project initiation phase critical decision analysis content

## 3.2. Interviews

Semi-structured interviews, personal meetings, group meetings, and follow-up meetings questions/documents using open-ended questionnaires are conducted to the project participants who joined design decision making process. What we are asking for is what the critical decisions are, how-why these decisions are taken in contract to other options at what time, and by whom.

Based on an interview with the mechanical designer of Connelly School Retrofit Project, we found that starting energy consumption reduction with an appropriate envelope upgrade is very critical. Half of the energy consumption reduction is achieved through insulation decision which is taken by architect, mechanical designer, and construction manager collaboratively due spatial, thermal, and cost effects. Consequently, they decided to insulate the building envelope from the inside which led them to reduce the biggest chuck of energy savings with 25% off. The main driver of insulating building from inside is to protect the historic view of envelope. However, this decision was not ideal in terms of the limitation on floor area and thermal storage behavior of the massive wall. Yet, the historic view and the tax credit criteria are the drivers of this energy efficiency decision.

### 3.3. Rapid Prototyping:

Development of the prototype is the future step of this project. It will be an iterative development and testing of process maps that will help system feedback.

## 4. Key Findings and Observations

As a consequence of case study reviews, it is more important to use multiple system integration appropriate to the inherent characteristics of a retrofit project rather than high performance technologies independently. Whole building design techniques provide architectural, mechanical, and electrical designers to integrate systems and make the operation efficient as designed performance. In order to improve the indoor environmental quality, the designer lets the systems work in different combinations according to different needs and seasonal conditions. Even though the system performance is critical, insulation is elevating the importance energy consumption reduction at first. The steps are recommended as below (

Table 2) according to different system design phases after the optimum insulation.

Table 2: Recommended MEP system decision deliverables by phase

| Phases | Conceptual | Schematics | Design Development | Construction Documentation |
|---|---|---|---|---|
| **Decision Scope** | What systems will be selected | Where the systems will fit into existing structure | Verify with the budget | Final Level of Detail |
| **Deliverables** | Selected system list | Locations, flows, and distributions | Cost fit | Final Drawings |

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# SUSTAINABLE DEVELOPMENT OF URBAN HERITAGE AT FORT KOCHI, KERALA, INDIA

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## Abstract

Many historic buildings and areas are being lost due to population growth, spatial expansion and area improvements in countries and cities that have expanding economies. Attempts at conserving such heritage have more, often than not, used tourism as the key to preservation. Indeed tourism can help preserve built heritage and revenues from tourism can fund and sustain conservation efforts. However, attracting tourists to historic built-form requires development of new infrastructure that can comprise the historical integrity of the main draw. In other words, a sustainable approach to historic preservation is often very complex.

In this paper, we present a case of sustainable conservation of a historic area in a developing country – India. Using this location – Fort Cochin/Mattancherry in the south Indian state of Kerala -- we choose to highlight the differences in the policy context in which historic preservation happens in the West and the rest of the world. Given the ongoing economic growth in China, India, Indonesia and Philippines the locus of preservation struggles to save historic heritage is shifting from the West to the East. Current knowledge about such struggles is clearly focused on the West and may not provide good guidance for effective strategies in the East. We believe this paper is a first step in filling an increasing felt void in existing literature.

We employed a qualitative case study approach for the research reported in this paper, using ethnographic surveys combined with data from secondary sources. We compare historic preservation efforts in two US cities and show that the highly successful approaches used there would not serve Fort Kochi/Mattanchery very well. Instead we propose a more contextualized approach that locates historic preservation within the broader framework of sustainable regional development. We believe that this approach could serve as a model for historic preservation-through-tourism efforts in developing countries of the East.

## I. Introduction

Built heritage of any region bear the imprints of history and reflect the culture and traditions of the past. Many historic buildings and areas are being lost due to population growth, spatial expansion and area improvements, especially in countries and cities that have expanding economies. One obvious challenge facing conservationists and preservationists in such contexts is this: preserve this historic building or area for what? And the common answer to this is “for tourism”. Tourism can help preserve buildings and areas and with the revenue generate make such conservation efforts financially sustainable in the long run. However, attracting tourists to historic built-form requires development of new infrastructure that can comprise the historical integrity of the main draw. In other words, a sustainable approach to historic preservation is often very complex. None of what we have stated above is news and many such struggles are well documented in case studies in published literature. But most of these case studies and indeed our knowledge of historic preservation are based on attempts at historic preservation in the West [1-5].

In this paper, we present a case of sustainable conservation of a historic area in a developing country – India. Using this location – Fort Cochin/Mattancherry in the south Indian state of Kerala. We choose to highlight the differences in the policy context in which historic preservation happens in the West and the rest of the world. Given the ongoing economic growth in China, India, Indonesia and a few other countries when contrasted with the economic contraction in the US and Europe, the locus of struggles to save historic heritage is shifting from the West to the East. Current knowledge about historic preservation with its inherent Western bias may not provide good guidance for effective preservation strategies in the new economies[3-7]. We believe this paper is a first step in filling an increasing felt void in existing literature. The rest of the paper is organized as follows. First we discuss the importance of conservation of historic buildings and for the use of a sustainable approach in doing so. Next we present a glimpse of the context, the uniqueness of the built form there and make a case for its preservation. Thereafter we discuss prospects for the area if no conservation efforts are employed and critique some ongoing conservation efforts. We conclude with a few policy suggestions that would help conserve this

## II. Importance of the sustainable development of historic cities

At a time of rapid urbanization and globalization, the conservation of historic cities is one of the most urgent and difficult challenges facing the field of heritage conservation. The task extends beyond the preservation of the architecture and landscape, and requires the careful management of change through adaptation of historic buildings and urban fabric to new forms of living, evolving land uses, and consideration of intangible heritage that contributes to the city's cultural significance. However, management of that heritage, within a framework of internationally recognized and appropriately applied standards, is usually the responsibility of the particular community or custodian group.

A primary objective for managing heritage is to communicate its significance and need for its conservation to its host community and to visitors. Reasonable and well managed physical, intellectual and/or emotive access to heritage and cultural development is both a right and a privilege. It brings with it a duty of respect for the heritage values, interests and equity of the present-day host community, indigenous custodians or owners of historic property and for the

landscapes and cultures from which that heritage evolved
Cultural significance is defined as "aesthetic, historic, scientific, social or spiritual value for past, present or future generations. It is synonymous with heritage significance and cultural heritage value which may change as a result of the continuing history of the place while understanding of cultural significance may change as a result of new information". Meaning that artifacts and spaces, also through their uses, are imbued with qualities and values, which need to be defined – and re-defined, by each generation– in order to arrive at sustainable interventions that protect and possibly enhance these values to groups of individuals, communities, and society at large [8].

Historic cities are the identity of cultural, social and economic development of a region. Urban heritage bears imprints of past civilizations. Changes in political policies, functions, upcoming infrastructure development should not erase the unique a well-tempered built-form vocabulary developed over the ages. In historic urban context, responsible urban development will be a combination of urban conservation, management renewal and redevelopment on the one hand and new development reflecting current norms and mores on the other [9].

## III. Case study context

Fort Kochi, located in the south Indian state of Kerala and known as the Queen of the Arabian Sea, has been an important place in the world map for voyagers and traders for centuries. It developed as an important port for spices, cashew nuts, tea, coir products and handicrafts. The city had trade relationships with Arab, Greek and Roman, Jews, Chinese and later European colonial powers. Travelers from these regions settled here and have had a great influence on the cultural and religious aspects of Kerala's social structure, and also on the built heritage of Kochi. Fort Cochin was the site of the first European settlement in India when the Portuguese established a fort here in 1500 AD., located not too far from Mattancherry**,** the nerve center of old historic Cochin. In the next few paragraphs we trace the origin and spatial growth of Fort Kochi.
Fort Kochi assumes great importance in world history as it has one of the best preserved histories of colonial times with its magnificent buildings, old road and rail network, tree-lined avenues, quaint little neighborhoods and residential settlements of different communities which thrived there. These attractions include are the houses from the Portuguese era, and the Jewish settlements of Mattancherry that house the Jewish Synagogue and the Dutch Palace that are over 400 years old.
Once a fishing village of no significance in the Kingdom of Kochi during the pre-colonial Kerala, the territory that would be later known as Fort Kochi was granted to the Portuguese in 1503 by the Rajah of Kochi , who also gave them permission to build a fort near the waterfront to protect their commercial interests. The first part of the name Fort Kochi comes from Fort Emmanuel, which was later destroyed by the Dutch. Behind the fort, the Portuguese built their settlement and a wooden church, which was rebuilt in 1516 as a permanent structure and which today, is known as the St Francis Church. Fort Kochi remained a Portuguese possession for 160 years. In 1683 the Dutch captured the territory from the Portuguese, destroyed many Portuguese, particularly Catholic, institutions including convents. The Dutch held Fort Kochi as their possession for 112 years until 1795, when the British took control by defeating the Dutch. Four hundred and forty four years of foreign control of Fort Kochi ended in 1947 with the Indian independence.

An eclectic mix of Portuguese, Dutch and British style houses from various periods of colonial rule line the streets of Fort Kochi. St Francis Church built in 1503 by the Portuguese as a Catholic church and where Vasco da Gama – the famous Portuguese sea farer --- was once buried, is now used by the Church of South India and is now deemed a monument of national interest. Since around 500 AD Arabian and Chinese traders sourced pepper, cinnamon, cardamom, cloves, sandal wood etc. from the Kochi region. Cultivation and trade concerning these valuable goods shaped the history of the region still until today. First the Arabian traders knew about these products, and they brought the highly wanted merchandise to Europe. Later, the Portuguese, then the Dutch, and afterwards the British fought for supremacy in this business.

*Historically significant events in this area*

One finds written documents about this area from about 600 AD. The area was inhabited by a multi-faith community with Hindus, Christians, Muslims and a Jewish minority peacefully co-existing. Its rise to regional prominence began when in 1341 AD a flood destroyed the then thriving harbor of Kodungalur. This flood also created the harbor of Kochi was created and the port –town that developed around it became a key stop in the global spice trade. The balance of power in the area radically changed around 1500 AD when the first Portuguese ships landed at the Malabar coast -- Vasco da Gama in Calicut, and Pedro Álvares Cabral in Kochi. One of the local rules of the regions, the Maharaja of Kochi had for long felt threatened by the other dominant local power, the Zamorin at Calicut. He hoped that by befriending the Portuguese, he could defend himself better against the Zamorin. So he welcomed the Portuguese. The Portuguese founded their first trading center in Asia in Kochi, but soon overthrew the Maharaja and made Kochi the first European colony in India. The period of Portuguese rule was characterized by religious strife – between the Syrian Christian church that existed here and the Roman Catholic Church that the Portuguese swore allegiance to [9].

The Dutch came to India in the 1600s. They landed in north Kerala and allied with the Zamorin of Calicut and conquered Kochi in 1653 AD. They integrated the port of Kochi into the emerging worldwide trading network of the Dutch East India Company. This integration combined with the Dutch policy of religious tolerance, ensured an upswing in Kochi's financial fortunes. However, the Dutch were keen on removing the Portuguese imprint on Kochi built form and replacing it with another one of their own. So they demolished over a third of the buildings built by the Portuguese and all churches barring two. In 1662, the Dutch killed the Raja of Kochi in a skirmish outside his residence, Mattancherry Palace. Soon after this they built a new fort in Kochi. This was followed by several decades of relative political calm and prosperity. From 1760 to 1790, regional wars devastated the city. Kochi was conquered by a major south Indian king Hyder Ali and then ruled by him and his son Tipu Sultan. In 1790, the British conquered Kochi in 1795, and blew up significant portions of the Dutch fort. The Dutch won Kochi back but signed a pact with the British in 1814 and as a consequence of this pact the Dutch left Kochi handing it to the British who made it a part of the Madras Presidency – making Kochi a part of the British empire. In 1947, when India became independent of the British, Kochi became part of India and was the capital city of the state of Kerala till 1956 [9].

## IV. Monuments in the Fort Kochi area[9]

*Dutch Palace*

Built by the Portuguese in 1557 and presented to Raja Veera Kerala Varma of Kochi, the Palace was renovated in 1663 by the Dutch. The palace with a *Bhagavathi* temple in the central courtyard is built like the typical Kerala style mansion - the *Nalukettu* - the home of the aristocracy, nobility and upper classes, with four separate wings opening out to a central courtyard. The palace is a two-storey quadrangular building that surrounds a central courtyard containing a Hindu Temple, enshrining the royal deity, Palayannur Bhagavati. Two more temples are situated on either side of the Palace dedicated to Lord Krishna & Lord Siva respectively. The palace has beautiful murals and a remarkable display of old palanquins. Though built by the Portugese, it is now known as the Dutch Palace, because it was renovated and re-built by the Dutch East India Company in 1663 AD.

*Jewish Synagogue, Mattancherry*

The synagogue at Fort Kochi, constructed in 1568 *by Cochin Jewish* community in the Kingdom of Cochin , is one of the oldest synagogues in the world. It was historically used by "White Jews" -- exiles from the Middle East and European . The synagogue is located in the quarter of Old Cochin known as Jew Town, and is the only one of the seven synagogues in the area still in use. It was built adjacent to the Mattancherry Palace temple (they share a common wall) on land gifted to the Malabari Yehuden community by the Raja of Kochi.

The synagogue was partially destroyed in the war of 1662, but was rebuilt by Dutch. In the mid-18th century, a clock tower was added. The synagogue is decorated with Chinese hand-painted willow patterned tiles from Canton in China and Belgian chandeliers. It has Hebrew inscriptions on stone slabs, great scrolls of the Old Testament, and ancient scripts on copper plates in which the grants of privilege made by the erstwhile Cochin rulers were recorded.

*St Francis Church, Fort Cochin*

St. Francis Church, originally dedicated to Santo Antonio, the patron Saint of Portugal, it was the first European church built in India. This church is a living historical monument, is still used for Sunday Mass and other religious functions and one of the main tourist attractions in Fort Kochi. Its history reflects the struggles of the European powers for supremacy in India from the 15th through 20th century. The church was originally a wooden structure dedicated to St Bartholomew within the fort built in 1503, by the Portuguese who came with Admiral Pedro Alvarez de Cabral. In AD 1506, the Portuguese Viceroy Dom Francisco Almedia was permitted by the Cochin Raja to reconstruct the buildings in stone masonry. Accordingly the wooden church was refurbished with bricks and mortar and a tiled roof was erected. This new structure was completed and dedicated to St. Antony in 1516 AD. When the Dutch captured Kochi in 1663, they used this as a Protestant church. They made some renovations to the building in 1779 but shortly thereafter the British captured Kochi. Though the British permitted the Dutch to retain the church, in 1804, the Dutch voluntarily surrendered the church to the Anglican Communion which renamed it as the St. Francis Church. The church became a protected monument in April 1923 under the Protected Monuments Act of India of 1904.

It is a modest unpretentious structure, and is a landmark of church architecture in India because numerous Indian churches have been built using the St. Francis church as the model. It has a simple rectangular plan with a gabled timber-framed roof. It faces the west, has a semi-circular arched entrance and windows above, and is flanked on either side by a stepped pinnacle. There is a bell-turret on the summit of the gable-front, divided into three compartments. Inside the building, the chancel is divided from the nave by a plain arched opening and the top of the chancel roof is crowned by two stepped pinnacles. Also, there are tombs set into the walls and the floor of Portuguese citizens (on the northern sidewall) and of Dutch citizens (on the southern wall). Vasco Da Gama died in Kochi in 1524 on his 3rd visit and was originally buried in this church.

*Santa Cruz Cathedral*

Santa Cruz Basilica, a Roman Catholic Cathedral, is also a living historical monument, endowed with Gothic style architectural and artistic grandeur and colors. Located close to St. Francis Church it is the 'capital church' of the diocese of Cochin.

*David Hall*

David Hall is an exclusive Dutch building located on one side of the Parade Ground in Fort Kochi . It was the residence of David Koder, a Jewish businessman, and hence the name David Hall. Built in 1695 by the Dutch East Indian Company, this hall is associated with Hendrik Adriaan van Reed lot Drakestein, a famous Dutch commander also known for his Hortus Malabaricus, a pioneering compilation of the flora of the Malabar Coast. Today the structure belongs to the Cultural History of Netherlands Overseas India. The building is in disrepair as several plans are afoot to save it from ruin.

*The Dutch Cemetery*

The 282-year-old Dutch Cemetery in Fort Kochi is the oldest European cemetery in India and has the remains of the many Dutch and English nationals that came and died in India. Consecrated in 1724, the cemetery has 104 tombs. It is now overseen by the Church of South India that also manages the St. Francis Church here.

*Bastion Bungalow*

Built by the Portuguese in 1667, Bastion Bungalow has been built into ramparts of a massive fortification wall. It is an Indo-European style edifice, reflecting Dutch architecture, erected on the site of Stromberg Bastion of the Old Dutch Fort, hence the name. The building blends beautifully into the circular structure of the bastion, has a tiled roof and a first floor verandah in wood along its front portion. Bastion Bungalow is a protected monument.

## V. Current redevelopment efforts: their strengths and limitations

Heritage walks shall be organized to revoke the existence of various ethnic communities which thrived in the region with their culture and lifestyles. With the promotion of Heritage tourism, Visual arts and Performing arts should also be developed side by side. This would help in further development and marketing of the heritage and cultural tourism. The existing heritage buildings, natural beach and other structures like the Chinese fishing net should be revived. The heritage walk linking major historic buildings and precints can be developed. The identified nodal points in the walk are (i) Chinese Fishing Nets, Fort Kochi (ii) Fort Kochi Beach (iii) St. Francis Church, Fort Kochi (iv) Vasco House, Fort Kochi (v) Santa Cruz Basilica, Fort Kochi (vi) Jewish Synagogue and Jew Town, Mattancherry and (vii) Dutch Palace (Mattancherry Palace), Mattancherry.

## VI. Strategies for sustainable development

*Eight crucial steps*

1) Undertake comprehensive surveys and mapping of the city's natural, cultural and human resources (such as water catchment areas, green spaces, monuments and sites, viewsheds, local communities with their living cultural traditions);
2) Reach consensus using participatory planning and stakeholder consultations on what values to protect and to transmit to future generations and to determine the attributes that carry these values;
3) Assess vulnerability of these attributes to socio-economic stresses, as well as impacts of climate change;
4) With these in hand, and only then, develop a city development strategy (CDS) or a city conservation strategy (CCS) to integrate urban heritage values and their vulnerability status into a wider framework of city development, the overlay of which will indicate A) strictly no-go areas; B) sensitive areas that require careful attention to planning, design and Implementation; and C) opportunities for development (among which high-rise constructions);
5) Prioritize actions for conservation and development
6) Establish appropriate partnerships and local management frameworks for each of the identified projects for conservation and development in the CDS/CCS, as well as to develop mechanisms for the coordination of the various activities between different actors, both public and private;

7) Implement a process of cultural mapping as a tool for the identification of the genius loci of historic areas in their wider setting;

8) Implement an enhanced impact assessment covering not only environmental issues, but also visual, cultural and social aspects.

**Four actions:**

1. Create a special website to facilitate communication and exchange on the Historic Urban Landscape approach of FORT KOCHI AND MATTANCHERY related to its development and implementation, in particular as a virtual platform for Local Governments and Site Managers to share views, ideas and knowledge.

2. Establish a working group comprised of institutional partners relevant to the development and implementation of the Historic Urban Landscape approach of FORT KOCHI AND MATTANCHERY, with a particular focus on those that can provide specialized skills and expertise to Member States requesting technical assistance.

3. Develop technical assistance packages which can be sponsored by bilateral donors and private sector parties, with an emphasis on lesser-developed regions, Encourage scientific research on specific aspects of the Historic Urban Landscape Approach of FORT KOCHI AND MATTANCHERY including Integrated Heritage Legislation; Urban Heritage and Integrity;

Compatibility of Contemporary Interventions; Limits of Acceptable Change; Strategic Assessment and Heritage Impact Assessment; Modern Planning & Design and Traditional Knowledge; Creativity and Making Heritage; Disaster Reduction and Adaptation; Private Sector Involvement; Documentation, Visualization and Presentation, to name but a few.

4. Organize conferences and symposia to foster international debate on the further development and implementation of the Historic Urban Landscape Approach of FORT KOCHI AND MATTANCHERY and to disseminate the state-of-the-art in research and practice, and also to make them known through publications in the virtual and real domains.

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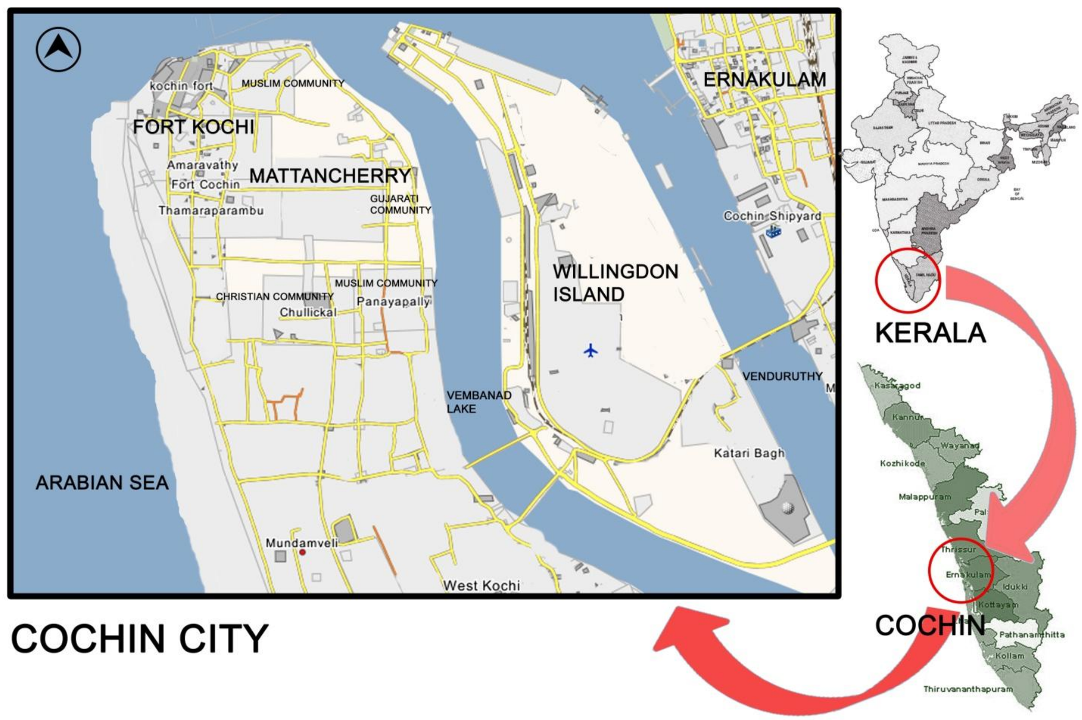


**Figure 1 Map of Fort Kochi and Mattancherry**

**Adapted from [9]**

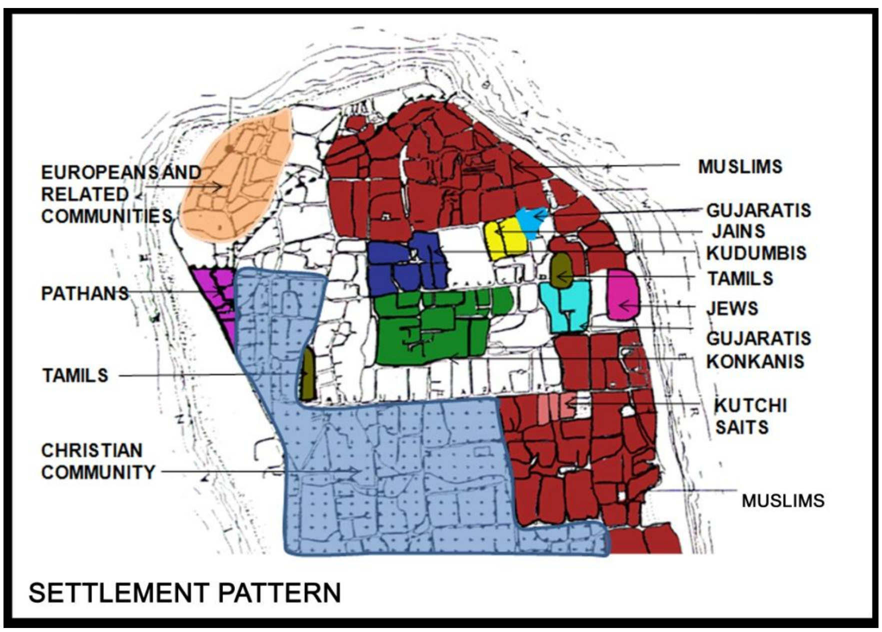


**Figure 2. Fort Kochi and Mattacherry showing settlement of different communities**

**Adapted from [9]**

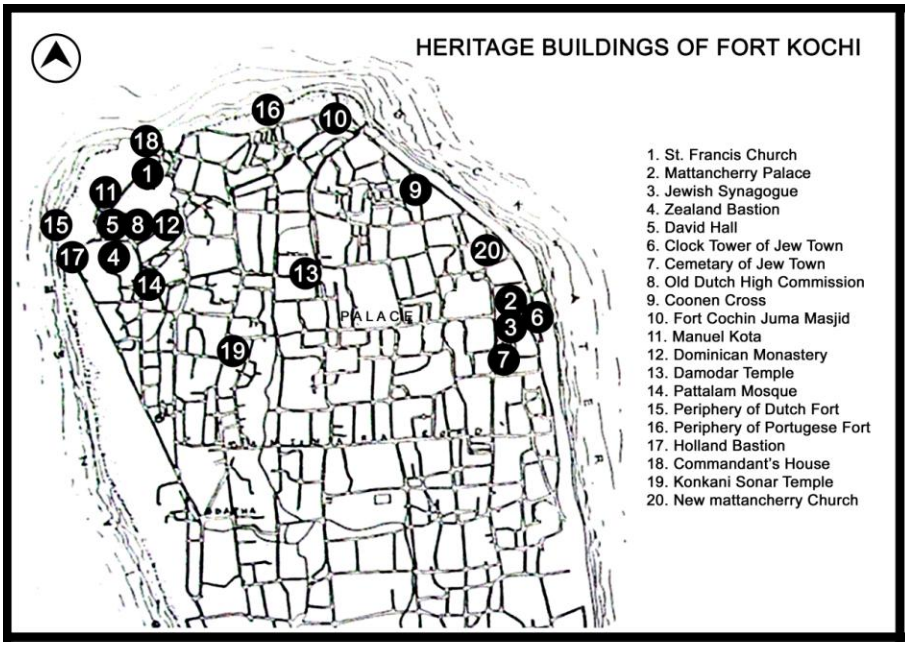


**Figure 3 Heritage Buildings of Fort Kochi**

**Adapted from [9]**

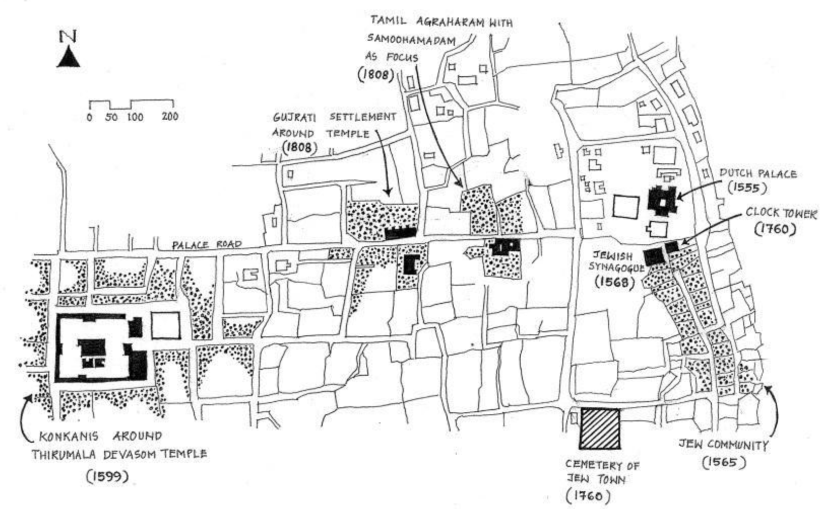


**Figure 4 Layout of the settlement showing major community settlements (A D 1808)**

**Adapted from [9]**

# INTEGRATING SPACE-SYNTAX AND DISCRETE-EVENT SIMULATION FOR E-MOBILITY ANALYSIS

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## ABSTRACT

**M**odeling and simulation of dynamic systems has been commonly used in the context of transportation, urban planning, and land use as being the basic tool for planners and policy makers. Vehicular movement modeling is one of the most popular models that deal with relevant aspects of urban regions and communities. This paper focuses on a particular mobility system; electric vehicles (EVs) clusters. It presents a study was conducted to simulate EVs population of the inner urban core of Newcastle-Gateshead via a developed 2D simulation model. The novelty of this study is the new approach proposed to simulate EV population in particular vicinity. This is by utilizing hybrid simulation technique (agent based modeling and discrete events) while applying space syntax theory and principles to predict the travel demand pattern of the urban system. The combination of these layers of modeling within the context of electrical mobility has proven successful in portraying the population and showed promising results. It aims at providing guidelines and recommendations to locate preliminary charging points and determine their numbers and capacities, which should be of interest for researchers, planning authorities and policy makers. This paper is a part of an EU project that focuses on simulating a part of the North Sea Region e-mobility system.

*Key words: Agents, Electric Vehicles, Discrete events, Simulation, Space Syntax*

## INTRODUCTION

Modern urban regions and particularly urban centers are the most complex networks constructed by human societies. They involve several layers of complexity and provide a matrix for economic and social evolution for the entire city hence the country (Buhl 2006). Since 1960's, many mathematical, statistical and logical models have been formalized to predict vehicular movement networks and relative applications. There is a reciprocal relationship between transport network and urban changes. Any change/ growth in roads network eventually influences the economic activities which in turn is reflected in the travel demand pattern of the particular location (Lacono, Levinson et al. 2008). For copious applications, configuring the layers of urban space and their inter-relations is a crucial matter for designers and planners. **M**odeling and simulation has been commonly used in the context of transportation, urban planning, and land use as being the basic tool for planners and policy makers. The representation of dense dynamic environments such as populated cities remains as a problem (Tecchia 2001) as they are highly complex entities to be virtually presented using real-world metropolitan data.

On another note, the environmental burden of these communities and particularly the transport sector had left no choice for many developed countries across the Organization of Economic Co-operation and Development (OECD) (IEA 2011) to work towards resilience and sustainability plans and schemes (ElBanhawy, Dalton et al. 2012 A). With the expected population growth rate, and rapid urbanization trend, we are putting tremendous pressure on the world's resources and high demand for land (Foley 2009). 2011 report, (Sousanis 2011) revealed that the number of cars on the world's roads surpassed one billion in 2010 which spurs the debate on what the rapidly-growing car population will mean for the world's economy and environment (Tancer 2011). Syntactically, many developed countries' local authorities, researchers, and policy makers have focused on the low carbon emissions vehicles industry and their market penetration levels considering alternative means of transportation (IMechE 2000) e.g. hybrid, electric, hydrogen/fuel cell vehicles (Herbert 2011). Electrical mobility (e-mobility) has been touted as a potential solution to the problem of increased CO2 and greenhouse gases emissions.

**Study Focus**

Likewise any publicly or privately operated mean of transport, EV system requires reliable soft infrastructure (regulation, business models, incentives, skills, community engagement) and integrated hard infrastructure (recharging points, smart grids, buildings transport systems) to viably support its operation (Beeton 2011). EV population is an independent complete mobility system that incorporates marketers, operation services, manufactures, batteries and compulsion technologies providers. Furthermore, the end user's perspective and feedback is highly considered so as to know the main enablers and hurdles of the system usability. This paper is part of a research project that aims at simulating EV system in metropolitan areas to investigate how to integrate charging points into urban infrastructure and how the planning authorizes and policy makers decide where to late charging points wherever needed.

**Study Approach**

The utilization of agent based modeling (ABM) has been widely used in vehicular movement network studies and traffic management analysis. Some hybrid models were developed integrating ABM to portray a specific phenomenon in transport networks Bonabeau, 2002); (Acha, 2011). As an alternative approach to predict the human crowd dynamics and vehicular travel demand models, space syntax analysis was used as the urban layer of several simulation models (Hillier, 1997); (Xinqi at al, 2008). Integration between space syntax and ABM has also shown interesting results in the area of pedestrian crowd flow and vehicular movement models (Penn and Turner, 2001); (Calogero, 2008); (Penn, 2003). The novelty of this piece of work is integrating the existing hybrid simulation technique ABM and discrete event (DE) with space syntax analysis to present EVs population in metropolitan areas. In the following sections of the paper, each in turn shall be discussed ended by a developed prototype tool.

In recent publications, (ElBanhawy, Dalton et al. 2012 A) explained the overall methodology of the research and the main paradigms of EVs population (ElBanhawy, Dalton et al. 2012 B). This paper follows the series of these publications presenting the new approach of modeling and explaining how a conceptual model for simulating EVs' drivers in metropolitan area can be developed and operated.

## EVs MARKET AND MOVEMENT MODELNG

Electric Vehicles (EVs) market is hampered by many factors (DfT 2011) which in return affect EV market penetration level e.g. cost, range, capacity, visual appeal speed, and lack of recharging infrastructure (Graham-Rowe 2012); (Garling 2001). Urban geography, market maturity and infrastructure have their effects on the market growth (JATO 2011). Furthermore, EV anxiety range- EVRA (Nilsson 2011) is considered to be also one of the main hurdles. EVRA basically exists due to the short full-electric range the EVs have (HMGovernment 2011). Full-electric range is the maximum distance a vehicle could travel without a need of charge (Eppstein 2011).This anxiety is significantly linked to how integrated and reliable is the charging infrastructure. Locating and estimating the demand for these charging points requires (1) a detailed analysis of the urban context, (2) deep understanding of the driving and charging patterns and behaviors, and how these two factors interrelate in metropolitan areas.

E-mobility is a sub set of the conventional mobility data. It is a small part of a large group which shares common paradigms e.g. roads network layer, some of the agents' behaviors and traits, goals scale, visualization and GIS purposes. Whereas, it has other unique features and parameters e.g. battery state, charging preferences, number of destinations and parking areas, that exist. Depending upon the applications and end users' drives, the simulation set up is formulated. In some applications, vehicle type is not an influential factor, EV and non EV will be typically replicated. Network and controlling rules will be applied to both like the case of traffic management/ impact analysis (ElBanhawy, Dalton et al. 2012 B). Whereas, other applications pertinent to air quality and noise, the vehicle type is affecting the simulation outcomes hence, the EV would be recognized (Hodges and Bell 2011).

## HYBRID SIMULATION TECHNIQUES

The concept of this study is to embed metropolitan area's vehicular movements into hybrid simulation while incorporating space syntax analysis (Batty, Dodge et al. 2000).To decide which simulation technique to be employed in the model, we need to understand the potential techniques and the different possibilities to integrate more than one method as inadequate representation of the detailed population structure can lead to spurious results. There are mainly three simulation techniques: (1) Agent-based Modeling (ABM), (2) Discrete Events (DE), and (3) System Dynamic (SD). The latter is used in the area of engineering design process. DE mainly revolves around the concept of entities, resources and block charts where queuing, waiting, servicing, and processing events occur while the system changes instantaneously in response to certain events (Maria 1997). This type of modeling roots to 1960s and it is used to portray entities flow and resource sharing which is useful in problems like services, manufacturing, logistics, business processes, etc. In DE, entities can be people, products, documents, calls, tasks, etc.(Borshchev 2004).

ABM is a decentralized approach of portraying emergent behavior of a crowd. In comparison to SD and DE, no global system behavior would be defined though an emergent behavior of a particular number of population/crowd can be depicted. This is based on individual autonomous heterogynous agents and which is why it is called the bottom-up approach (Li, Sim et al. 2006). Agents work to find solutions (Chen 2009), learn from their experience and adapt to better suit the environment (North 2010). In former publication, the ABM was the proposed technique to portray the EVs drivers' behavior and charging patterns (ElBanhawy, Dalton et al. 2012 B).This was due to several reasons one of which is the interdependences problem. Using ABM does not require knowing a lot about the level of interaction/effects/dependencies/global sequence at an aggregate level. By having enough knowledge about individual participants performance, the phenomenon can be depicted (Borshchev 2004). A hybrid model is proposed as it might better serve the present problem due to the fact that the main paradigms of the model are being a large-group simulation of active objects that has timing, sequential events, and individual behaviors.

In DE, entities in the flow are abided by some rules and they encounter some events. In a case like EVs simulation, these entities are the EV agents where we can depict the charging behavior and driving pattern of each driver. Hence, in such system, entities enter the system (the road network), use their batteries (each one starts with different state depends), enter service (charging points), queuing and delays occur (depends on the battery state, power, and availability), then the entities exit the service (finish charging), drive around the system heading to difference destination(s).

Having such hybrid model, where the creation of the entity corresponds to the agent creation enables the model to realistically simulate EVs population. The event of entity creation happens once the EV comes out of the source (origin) going through a path (route) and encounters some events (roads intersection, charging points). The creation of agents facilitates messaging protocol. The agent has the ability of checking its battery state and requesting a service (charging) via sending messages/ updates (the battery is almost flat, needs charging).This messaging protocol happens between the agent and DE system (environment elements). Once the agent requests a service, this associates moving from state to another (fully charged to need charging). Till this service is tackled, the system receives a message that an entity in the flow (queue) and needs to get serviced. Eventually, and based on a sequence and specified rate, the service is conducted, hence the entity gets the requested service, updates the agent, the agent moves from the current state to another (need charging to fully charged) and so on.

The importance of having a hybrid model appears when the agent's state changes depending on a DE and/or visa verse which requires a link/messaging protocol between the entity/system and the agent, hence the present study incorporates this technique. Accordingly, the platform used has been selected among many intuitive and simple available simulation tools. The selected commercial platform is AnyLogic; it is cable to support hybrid models, simulate micro-dynamic large-group simulation, requires less coding for adding IF THEN rules; and simulates societal and behavioral models.

## SPACE SYNTAX

In last decades, space syntax has been known as an alternative computational language that is used to spatially pattern the modern cites and analyze the topological relationships of settlement spaces (Hillier and Hanson 1984); (Hillier 1994). Different shapes of relations and levels of interactions between spaces each other and or with society, have superbly shaped the space syntax notion and its principles in analyzing the spatial patterns of cities (Jiang and Claramunt, 2002). Within a given built environment (system) and with its segmental representation of roads network, the virtue of space syntax theories and techniques can be used to quantify the properties of the space arrangement and measure its level of integration, accessibility and connectivity and depth. (Hillier and Hanson, 1984). Figures (3a and b) represent the connectivity and depth graph of the study area, explained later this paper.

Space syntax analysis considers on urban environment as an interconnected space; everywhere is linked to everywhere else (nodes/ points not regions) and there are always choices of routes from any one space to any other space (Hillier and Hanson 1984). The characteristics of the path system can be obtained by analyzing the shortest paths between all pairs of nodes. In transportation and land use context, the spatial configuration of simulation objects is a crucial issue due to the observed correlation between graph-based configurational measures of street networks, represented as lines, and vehicular and pedestrians navigational choices, observed movement, and flow patterns (Hillier and Iida 2005). It is observed that this correlation could strongly provide great insights on understanding cities and visualizing its impact within the field of urban studies, urban planning and urban economics (Law, Chiaradia et al. 2012).

**Angular Segment Analysis – ASA**

Many studies were conducted on the human movement behavior with respect to angularity. (Kim and Jaepil Choi 2009);(Golledge 1995) pointed out that individuals tend to minimize angular deviation from a straight line to destination as human tend to make the least physical effort. Turner pointed out that ease of directional change can be varied as turning angle, and proposed Angular Segment Analysis methodology that applied the shortest angular path based on angular depth to segmented axial map (Turner 2001) As defined by (Turner and Dalton 2005), ASA is the shortest angular path about each pair of origin-destination segments within the network. Recent related research reveals that ASA methodology shows more remarkable predictability for the actual movement pattern than existing traditional space syntax methodology (Turner 2007).

## CONCEPTUAL MODEL

The development of the model is a prolonged phase and has passed through several trials; each trail has guided the authors and showed a better direction. Early this paper, modeling layers have been explained, this section reciprocates by showing how these layers are developed in the pilot study. The study covers most of the technical and behavioral assumptions and the set-up needed to simulate the EVs population in metropolitan areas though in a small scale and less complicated and correlated to real-world system. It studies the concept along with the procedures needed to build the simulation model.

The inner urban core of Newcastle-Gateshead area with a total square area of 500KM, is the selected study area as highlighted in figure (8). Newcastle city is one of the greenest cities of the UK (Jha 2009). The Northeast is to become the UK's electric car capital, with plans to install up to 1,000 charging points around Newcastle and Gateshead over the next two years. Local authorities and universities have been active in the context of low carbon emissions vehicles research and development with a proven successful in providing initiatives and schemes and participating in green/smart programs. The simulation input data is based on the information about EVs' drivers and their usage which is provided by CYC back office (CYC 2011), the EVs local service provider for the UK North East region.

## Urban Layer

ASA is utilized and applied to the study area. The entry direction of the flow/ vehicles is important as this will count for the entire calculations. It starts with drawing the road centerline map of Newcastle urban core streets which is the approximate skeleton of urban network (Jiang 1998), figure (1). All streets are drawn as segments; each should be connected to the other by intersection angle. Calculating the segment depth via angular analysis can be done following (Iida and Hillier's (2005) convention. Intersection angles between segments vary between 0-180 degrees, which are assigned to values from 0-2, respectively. Figure (2) demonstrates the way calculating the depth of 3 segments presenting a part of roads network that starts from A and ends with E.

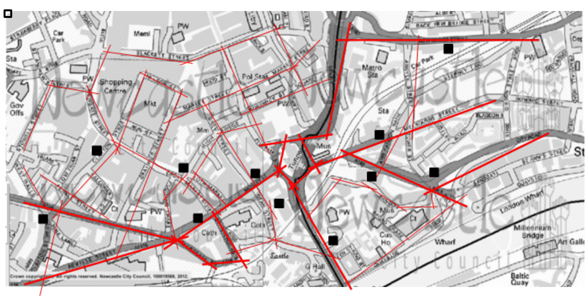

Figure 1: Axial map of the inner urban core of Newcastle

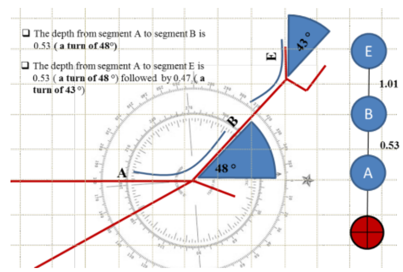


Figure2: ASA calculation technique

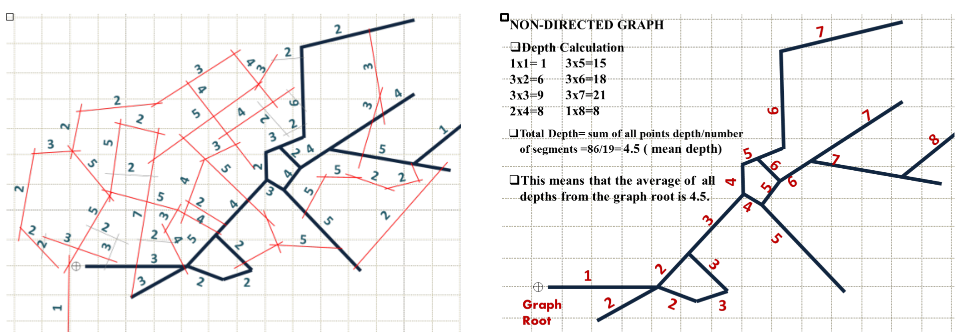


Figure 3a and b: Connectivity and depth maps of the study area

Newcastle Inner urban core segment map with angular mean depth of each segment from the graph root is calculated with active charging points located; figure (4). These values are used to predict the vehicular movement within the simulation due to the proven correlation between ASA and predicted movements. By using these values, the vehicle tends to take the less angular depth cumulatively in its trip. So once the agent reaches an intersection, it has to decide which way to go, figure (5). In the model, the authors pre-calculated the shortest routes, total mean depth, which reflects the angular mean depth values for all possible routes (holistic approach). Another approach might be taken which makes the computation more difficult when this task is left to the agent to calculate in each intersection within the simulation the angular depth and shortest route.

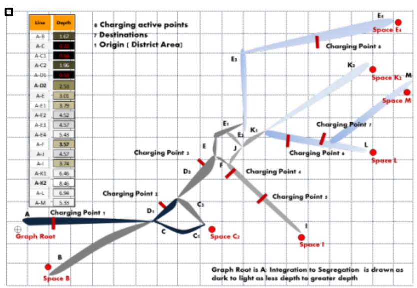

Figure 4: schematic Map showing the ASA of all streets

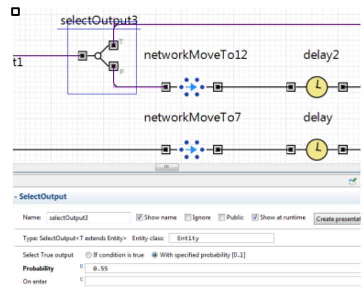


Figure 5: Intersection point and ASA

Via coupling simulation mode with configurational analysis techniques, the knowledge of possible urban patterns can be exploited; hence the movement can be predicted. Numerous urban and planning studies and analysis can be conducted employing such integrated model (Hillier 1994).

## Simulation Assumptions

Simulation modeling is an evolving process; it doesn't all being created at once. It starts with a simplified model with a less detailed set up, intuitive assumptions, and more limitations, and the more the model is developed, the more mature, detailed, high level of abstraction the simulation model reaches (Borshchev 2004). Assumptions and variables, table (1), are studied and tried. The model is an interactive tool; it can accommodate variations to provide different scenarios.

Table (1): Pilot study assumptions

| Assumptions | Pilot Study |
|---|---|
| Battery State | The agent starts its day with a state. The battery states are assumed ranging between 5 possible options for instance: 30%, 50%, 70% and 90% charge following uniform distribution approach. This basically relates to whether the agent has recently charged their vehicle using domestic charging. Once the EV battery reaches 20%, the minimal state, eventually the agent has to stop for charging otherwise the car will stop. |
| Charging Points | Charging points are presented as services with a delay time that various between (1, 1.5, 0.5) triangular distribution which presents the different states the charging post can perform (available, almost available, fully occupied), depending on the demand which reflects the time needed for charging. |
| Simulation Measure | The model counts the number of stopped vehicles in the system. Once the vehicle turns into red this means it is in a critical battery state and has to be charged as soon as possible. With the assigned rate, if the vehicle is not charged by that time, it will turn into grey which means flat battery. The model counts how many number turns into grey yet not calculating where they stopped in the road network. |

The possible charging scenarios as per the real EVs population are (1) charging at home (domestic charging), (2) on-street charging (publicly available charging), (3) charging at work. In this model, the first two scenarios are portrayed.

The full electric range of an EV depends on many factors e.g. the battery type, load, traffic conditions, weather, the weight and type of vehicle, the performance demands of the driver (driving style) and mode of driving.

Based on the rate of consumption, the battery state will change from fully charged to half charged to flat. Nissan LEAF (Nissan 2010), 24 kWh battery pack, in city traffic pattern has been taken as a reference in the model. The following assumptions were considered:

- All electric range: 105 Mile-169 KM/ Speed 24 mph or 39 km/h.
- Time needed to charge: 8 hours at 220V.
- The battery starts with 100% charged and lasts for 4.24 hrs. This means that 1% of the battery is consumed after 2.55 min. A flat rate is considered. Hence the model rate is 2.55

## Developing the Agent Architecture

The model is built based on the travel-dairies of the North East EVs' drivers who live /work within Newcastle. The model's update time-interval is a daily-based update (24 hours) which is the required rate needed to examine the system.

Agent's attributes/algorithms are the mechanisms underlying ABM; they are developed and pre-assigned (Helbing 2011).They are mainly related to O-D matrix and the decisions to be taken within the route, table (2). The simulation path is the chosen route within the DE environment. Operating agent architecture passes through stages; the pilot study performs the first step; whereas, the final model includes more complicated configurations. Table (2) depicts the state of both models.

Table (2): Final model Vs Pilot study assumptions

| Assumptions | Model ( future work) | Pilot Study (present study) |
|---|---|---|
| Agents Behaviour (Origin) | On a daily basis, agent starts new path with new destination(s) from its origin. Homes are selected and limited to the basic demographic-usage information provided by CYC. | All agents are generated from one source as all are coming from same district (Flow direction). Four possible destinations (1) Akenside Hill Queen Street, (2)New Bridge Street,(3)Melbourne Street,(4) City Road A185 |
| Agents Behaviour (Destinations) | Possible number of destinations is calculated based on the daily average mileage of UK drivers (41.9 Mile/day) (Aduk 2000). It is limited to 4 destinations /day including home trip. | Each agent goes to ONLY one of the destinations. This is based on a probability in each intersection based on ASA as presented in figure (5) |
| Agents Behaviour (Decisions ) | The first decision the agent takes is to check the state of the EV battery hence the charging schedule is planned ahead. This process happens every time the agent reaches a new destination. | The agent decides to charge or ignore and continue based on its battery state in case it passes by a charging point on its way. Depends on the percentage of charge it will stop to charge or it will |

## AnyLogic Model

In the agent model part of Anylogic, a state chart is used to design the agent architecture where all the above-mentioned attributes and definitions have to be built in. Sschematics and network diagrams of the EV system were developed. Sources and sinks indicate Origins and Destinations matrix (O-D matrix). Each EV follows the state chart which transfers it from a state to another based on some orders and decisions taken when certain events happen (DE) via adding IF statement in some cases; figure (6). Each EV has different state of battery that it starts the route with *(blue color with different percentages that range between 30%-70%)*. Transition happens between states via *(Time out)* condition; based on the consumption rate. It moves to yellow (driving) to red (needs urgent charging) to grey (flat battery) figure (7).

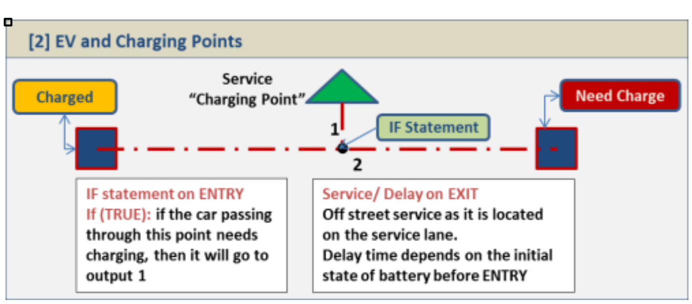


Figure 6: State transition

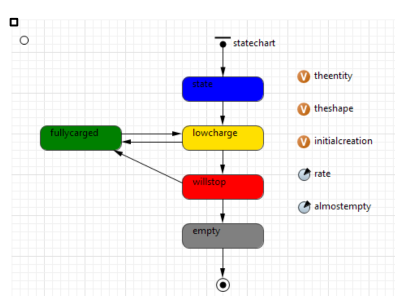


Figure 7: Agent State-Chart

The model consists of two parts: logic diagram and simulation presentation. The logic diagram is the network which is the main environment of simulation. The road network is presented e network works as a DE simulation and the entity is created at the source. Each entity once created, generates an agent with it. This combination provides the DE to simulate the road network system in terms of paths, delay (charging), and destinations (sink) where the agent facilitate having individual attributes which are ( battery states), state transition timing, and routes, figure(9) .


Figure 8: Newcastle Upon Tyne-Inner Urban Core (500 KM2) (www.maps.google.co.uk)

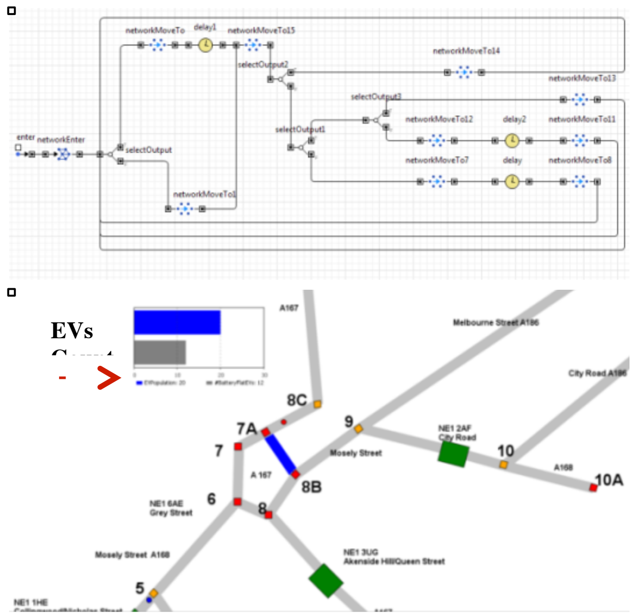


Figure 9: 2 models created by AnyLogic

## MODEL INTERIM OUTCOMES/APPLICATIONS

The model shows interesting and promising interim results. With a less-complicated version of simulation, the model reveals a prominent framework for EVs charging infrastructure planning purposes by providing a spatial decision support tool. The simulation of the partial Newcastle EVs system shows the possibility of examining the integration of charging infrastructure. Calculating the number of the stopped vehicles and knowing where they stopped within the system indicates and reflects how integrated is the infrastructure of the study area. By increasing the level of correlation between the real system and the virtual simulation, planners can examine whether the current charging points can accommodate the current demand and future generation or there is a need for new charging points to be located and if yes, then how many and where to be located.

## DISCUSSION AND CONCLUSION

Investigating and predicting the consumers' response is a significant challenge EV marketers are facing; however, the roll out of intelligent infrastructure, creation of innovative service models and changes in consumer behavior are all positive transformations and indicators for a better EV market penetration. EV market is on the verge of expansion and maturity. The use of simulation modeling to portray the EV populations in metropolitan areas can potentially assist planning authorities and policy makers to better evaluate the system usability and plan for future stream. In return, this shall support the market as providing accessible and high visible charging network generates interest amongst consumers and encourages uptake. The integrated vehicular model proposed in this paper has allowed us to develop a more realistic simulation of EVs population behavior in metropolitan areas. In the virtue of space syntax theory (urban layer) and hybrid simulation modeling (charging behavioral model), a conceptual model was developed to propose an approach to examine the level of integration and reliability of the existing charging infrastructure. The model shows how these two layers are correlated and strongly linked to portray the phenomenon. Main streets of the inner urban core of Newcastle were modeled along with the active charging points that serve the core area which is a preliminary version of the EVs system showing the overall picture of the agent system design integrated with DE within topological and geometric urban analysis.

**Future work**

Other factors regarding the iteration time, number of agents, charging schedules and types are to be considered incorporating other variables e.g. number of users and charging points number/ location to study all possible scenarios. Hence, new measures can be deliberated as the time the car waits to get charged in the simulation (queue), no of over-used and under-used charging points and the use of publicly available charging points rather than the domestic and at work

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# Building Sustainability into the UAE: ESTIDAMA

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Estidama, meaning sustainability in Arabic, is an initiative developed and promoted by the Abu Dhabi Urban Planning Council (UPC). The Plan Abu Dhabi 2030 Urban Master Plan includes sustainability as a core principle. The leadership of Abu Dhabi recognizes, however, that the unique cultural, climatic and economic development needs of the region require a more localized definition of sustainability, and they are progressing the principles and imperatives for sustainable development through Estidama, launched in 2008.

A need was identified for planning, design, construction and operate sustainable developments taking into account the traditions embedded within the local culture on one hand and the strong climatic nature of the region on the other. Estidama's main goal is preserving the physical and cultural identity of the region, while improving quality of life on four equal pillars of sustainability: Environmental, economic, social, and cultural. Estidama is put forward as not just regulations or a rating method, but a vision and a desire to achieve a sustainable way of life in the region.

This study analyses the significance of the vision and strategic approach for sustainable development of the region, addressing the economic and environmental needs emphasizing regional social and cultural characteristics.

Keywords: Sustainability, Estidama, Sustainable development.

**Introduction**

When The Shard skyscraper in London opened on 5th of July 2012, it was the tallest building in the EU. At the time, it was however already surpassed in height by 15-odd towers in Dubai. Such statistics say a great deal about property development in the United Arab Emirates. While providing great opportunities for grandiose architectural feats, such ambitious construction does not inherently lean itself to the best global standards of environmental sustainability.

In many aspects of life, the UAE is one of the most planned countries in the world. Its attempts to diversify economy away from oil are well known, and progress in this respect has won much admiration worldwide. However, emphasis on sustainability in particular has seen a recent increase in the Emirates. In this growth-driven country, it has been realized that development must be driven with and by sustainability.

The world has been in a process of transformation for over two decades, associated with the need for action to mitigate climate change and global warming. In this new paradigm, sustainability is an emergent behavioural and structural attribute with many components including a social and cultural dimension.

The sustainability movement started in the early 1970s, although it diffused unevenly around the world. One crucial challenge has been identified as a change of mindset and increased awareness by communicating the importance of the problem the world is facing, offering solutions to current wrong practices. It is realized, that sustainability can only be achieved through living within the limits of the earth's capacity for consumption while minimizing, recycling waste and eradicating pollution that human activities generate.

The built environment is a chief contributor to the sustainable development and in many ways takes a large share of the challenge. Construction projects from design, through construction and operation, to demolition stages constitute an immense factor in human impact on the environment. Consequently, sustainable development is now the stated policy of most local, national and international political bodies, and of much industry and commerce.

There is no question that it will be difficult to transform to a low-carbon economy, being liberated from fossil fuel dependence. However, there is a growing commitment to reverse unsustainable trends in development, and it acknowledged that transition will take time and at some cost.

**Knowledge Society and Culture-sensitive Sustainability**

The importance given to sustainability in Abu Dhabi is appearing in parallel to another national vision, that of the Knowledge Society. For achieving a sustainable and fruitful development, status of knowledge is central. Development and prosperity of countries highly depends on the quality and level of knowledge and knowledge infrastructure. Education plays a central role in any successful strategy to promote sustainable development.

A knowledge society is a society that is nurtured by its diversity and its capacities. Every society has its own knowledge assets. History and anthropology teach us that since ancient times, all societies have probably been each in its own way, knowledge societies. It is therefore necessary to work towards connecting the forms of knowledge that societies already possess and the new forms of development, acquisition and spread of knowledge valued by the knowledge economy model. (Unesco World report, 2005)

In the sustainable knowledge-based economy, the key strategy for implementing the paradigm of sustainable development is eco-innovation. Eco-innovation reduces the use of natural resources and of ecosystem services, material, energy and information. Any extraction, processing, distribution, consumption and re-use, or recycling of natural resources can be a starting point for the development of eco-innovations. The research shows that the biggest resource efficiency gains can be achieved easier in the upstream part of the supply chain, i.e. in the production of base materials and by reorganising the ways products and services are used. (Michałowski, 2012)

Sustainable development is conditioned by ethical aspects in functioning of the organizations or the countries implementing a sustainable knowledge-based economy. Increasing the awareness in environmental issues should be accompanied by ethical reasoning and implementation of intergeneration justice. A code of ethics may encompass responsibilities of the organizations and people to other living beings and to the environment, as well as the need to preserve ecosystem services for society and economy. Ethical and training programs need to be promoted to spread and broaden the knowledge and also increase sensitivity and awareness of the public.

For a society to pursue their goals and realize their values, they have to recognize the contours of their new historical terrain, the world they live in. Only then it will be possible to identify the means by which specific societies in specific contexts can pursue their goals and realize their values by using the new opportunities and technologies. Using the technology alone does not in itself amount to much social change. It depends where, by whom, for whom, and for what technologies are used. In order to use the technologies to the best of its potential, and in accordance with the projects and decisions of each society, we need to know the dynamics, constraints and possibilities of the new social structure associated with it: the network society. (Castells & Cardoso, 2005)

**Role of Sustainability in UAE growth**

The UAE is famous for several property developments of almost unprecedented ambition. The city of Dubai in particular has emerged as a 'global city' and business hub. However, with the slowing of the UAE construction boom and the rapidly changing global economic landscape, reality seems to have set in, triggering a reassessment of the future expansion blueprint for the Emirates. For the future, economists predict a slower, more sustainable UAE development than in the period leading up to the crisis (The National, 2010, 7th Oct.)

The Prime Minister of the United Arab Emirates, His Highness Sheikh Maktoum has declared that the UAE is equally committed to building a sustainable environment while supporting economic growth. His Highness Sheikh Maktoum also emphasizes that the UAE will continue to invest not only in hard infrastructure but also in soft infrastructure, with a sharp focus on education, healthcare and a culture that promotes research and development. The Prime Minister also points out the importance of trade, and also recognition of the importance and resilience of a knowledge-based economy as a key driver of sustainable growth and opportunities (Gulf News, 4th October 2012). His Highness Sheikh Maktoum declared that until 2050, emerging markets will be the main engine of global economic growth with trade flows infinitely more connected and goods, services and people more mobile than ever before in the new world order. "Dubai and the UAE sit at the intersection of one of the most transformative moments in geo-economic history in more than a century: the gradual but inevitable shift of the economic centre of gravity from the West to emerging markets and the rise of new trade markets. Our Green Economy Initiative announced earlier this year reaffirms our commitment to diversify energy sources and preserve the environment while strengthening our competitive position. Through this initiative, we aim to become a world leading centre for the export and re-export of green products and technologies. While we recognise the profound importance of safeguarding our identity and traditions – keeping sight of who we are and where we come from – we embrace the possibilities the future presents for our people, our city and our country." (Gulf News, 6th October, 2012)

The emirate of Abu Dhabi is taking steps to reassess its 2030 Economic Vision, acknowledging slower economic and population growth due to the impact of the global financial crisis, a government bond prospectus revealed in August 2012. The plan is a blueprint for diversifying the emirate's economy away from oil. Similarly, under the Dubai Strategic Plan (DSP) 2015, Dubai has dropped financial services and construction as its core focuses for expansion.

Reduction of greenhouse gas emissions is particularly challenging due to the regions cooling needs, a basic necessity in a hot arid environment. The need to desalinate seawater, and an energy intensive industrial base are other regional challenges being addressed.

The UAE Government states that clean energy takes a central position in their development strategy and that they are innovating solutions in energy efficiency, water efficiency, building standards, and sustainable development. These activities have come together in the announcement this year by His Highness Sheikh Maktoum, Prime Minister of the UAE, stating that the UAE is embarked upon a strategy of pursuing a Green Economy for Sustainable Development.

This vision is driving a range of important initiatives across the UAE:

- The UAE has adopted the first mandatory building efficiency codes in the region, including mandatory efficiency standards for cooling.
- Abu Dhabi and Dubai have set the region's first renewable energy targets, and 2012 saw the opening a 100MW concentrating solar plant, one of the largest in the world.
- Masdar City, a world-first low-carbon urban development in Abu Dhabi powered by renewable energy and a test bed for cutting edge clean energy and efficiency technologies is being built.
- The Masdar Institute, established in collaboration with the MIT, is the world's first postgraduate university solely dedicated to clean energy technology. The Emirati student body is roughly half women, and these students are already generating new clean energy technology and intellectual property.

The UAE is also a major investor in clean energy internationally, for instance a new concentrating solar power plant in Spain opened last year as part of a joint venture between Masdar and Sener.

**Need for a Sustainability framework that fits the local context**

A wrong impression of the sustainability concept may be given by implementation without sufficient attention to local variations. Analyses of the project experiences of the author's industry experience in UAE developed findings demonstrating that projects working with LEED consultants who are hired from overseas and have limited or no experience of local environment, climate and culture, delivered poor consultancy lacking the needs of the real sustainable development of the projects. Without analysing the building environment of the region with all aspects, the 'sustainability' efforts resulted in costly developments far from being sustainable due to overly ambitious sustainability goals. Several projects lacked the simplest passive design approaches with almost no additional cost. Selection of inapplicable or expensive add-on green technologies increased the costs without adding any real sustainability gain or achievement. Due to improper implementation of World's leading sustainability systems in many projects increased the belief that sustainability at low cost and high efficiency is almost not possible.

**A sustainability framework tailored to the region's needs; ESTIDAMA vs other leading systems used in the region**

The Pearls Rating system of Estidama is the outcome of awareness at the governmental level on the need for a sustainability framework tailored to the region's needs for a sustainable future development. A framework, in order to deal with an environment that is really unique in terms of culture and history, as well as its water and energy consumption. The aim is to find the best system that fits the unique environment by using the best practices appropriate for this region.

There are several sustainability frameworks currently being implemented in the region such as LEED and BREEAM, having similar core idea and approaches. But implementation of these widely depends on many factors such as local physical characteristics, as well as soft factors such as social and cultural characteristics.  Soft factors are generally overlooked by the construction practitioners ending up with designs and structures not in fit with the local patterns. Another misconceived construction practice has been implementing the sustainability frameworks without critically analyzing the different physical characteristics of regions and adaptation. Such projects ignoring the life cycle costing issues, regional parameters, social and cultural factors ended up with unnecessary or wrong investments, wrong designs, technologies and materials. The core of Estidama is a sustainability framework for Abu Dhabi, tailored to the characteristics of the region that will allow adaptation as new understanding evolves.

Estidama Pearl Rating was planned as a system that learns from its predecessors; the BREEAM rating system (British Research Establishment Environmental Assessment Method); and the LEED rating system (Leadership in Energy and Environmental Design). The intent was learning from mistakes and successes, and adapting these in the development of a new system appropriate to the environmental and cultural differences of the Emirates.

Estidama is a government initiative developed by the Abu Dhabi Urban Planning Authority and has just been launched in 2010. On the other hand BREEAM has a mission to provide relevant research and information to the building industry as a whole. Whereas LEED, developed by the United States Green Building Council (USGBC), which is a national non-profit membership body, is a voluntary, consensus-based, market-driven program that provides third-party verification of green buildings (www.usgbc.org).

Estidama is based on the Pearls Rating System. Unlike its predecessors systems, the Pearls Rating System is not a standalone document, but part of the Pearls Design System, which includes a complementary design Guide and supplementary Application Guides for public works, parks and infrastructure. Like LEED and BREEAM, the Pearls Rating System for Estidama includes a number of rating systems assessing buildings, villas, and neighborhoods. (Elgendy, 2010)

The Pearls Rating System is also strongly linked to the Estidama Integrative Design Process **(**EIDP), which seeks to promote the new concept of Integrated Design process (IDP) as a design approach amongst design professional by encouraging design coordination at the early stages of the project. EIDP is not only part of the Pearls Rating System, but it is also set to become part of the development codes as a prerequisite for all projects types, requiring all projects to carry out a number of analyses before the design process is permitted to begin. These analyses involve solar and contextual analyses, Energy efficiency design strategies including preliminary energy modelling, water budgeting, simple material strategies, and an analysis of potential for habitat connectivity. Estidama is planned to become one of the world's most progressive Green Building Initiative, to formally adopt the Integrated Design Process, but the first to make it mandatory. (Elgendy, 2010, estidama.org)

The Pearls Rating System has many similarities with the LEED and BREEAM rating systems, yet it is a system that is quite progressive and distinctly local, for example, the Pearls Rating System's emphasis on post-occupancy assessment indicates that it has learned lessons from other rating systems in designing a system that assesses results rather than intentions. (Elgendy, 2010)

The combination of mandatory enforceability of parts of Pearls and the incorporation of Pearls within Estidama's larger development framework, together with Estidama's efforts to promote an Integrative Design Process and the efforts by the market-driven Emirates Green Building Council, all have the potential to accelerate the market's adoption of green building practices at a faster rate than perhaps seen in the United States and the United Kingdom over the last 20 years. (estidama.org)

More than just a sustainability program, Estidama aims to be symbol of an inspired vision for governance and community development. Specifically, Estidama attempts to redefine how a contemporary Arab city should look and function, and to encourage sustainable growth, to encourage protection of the natural environment of sensitive coastal and desert ecologies, to re-emphasis the city's stature as a capital city of the United Arab Emirates, and to enable the urban fabric and infrastructure to enforce the local values and culture of this Arab community. These broad goals are tied to Estidama through a number of key performance indicators measuring energy use, water use, waste generation, carbon footprint, and biodiversity, amongst others indicators.

The Abu Dhabi Urban Planning Council (UPC) has worked with the team guiding Estidama to assure that sustainability is continually addressed through four angles: environmental, economic, social and cultural. Planning permission from the Abu Dhabi Urban Planning Council (UPC) is required for all strategic developments in the Emirate. The Development Review Process ensures individual developments knit together and advance Vision 2030, and at the same time are aligned with the Estidama requirements. A separate document - Planning for Estidama - has identified Estidama-related submissions for each stage of the development review process. These submissions ensure that projects are on track to achieve the required Pearl credits. After a project receives Detailed Planning Approval, then the full requirements of the PRS Design Rating become applicable. Achievement of the Design Rating is required before obtaining building permits with the Municipalities. (estidama.org)

**Energy Code in Abu Dhabi for Environment-friendly Buildings**

Abu Dhabi Department of Municipal Affairs (DMA) is developing a building code and Environment Health & Safety Management system for the construction sector that provides a robust regulatory framework to deliver safe, quality and environmentally sustainable buildings. (Abu Dhabi Guide to the use of: the International Building Codes, 2011)

These codes form a new system for building requirements and specifications that would boost the sustainable development drive in the emirate by implementing the world's best practices in construction systems. A key component of the codes is the Abu Dhabi International Energy Conservation Code which achieves energy efficiency targets established by the United Nations for extremely hot climates.

The codes aim unified and consistent building codes across the construction industry in the Emirate leading to longer lasting and more energy efficient buildings that offer long term cost savings.

This locally developed Code Guide, used in conjunction with the adopted building codes, establishes minimum regulations for prescriptive and performance-related provisions as they apply to the Emirate of Abu Dhabi. It is founded on broad based principles that make possible the use of new materials, building designs and methods of construction. This Code Guide is fully compatible with all the adopted model International Codes® (I-Codes®) as published by the International Code Council (ICC)® and planned to be applied after amendments to comply with local conditions of the emirate.

Another initiative in Abu Dhabi is the sustainable renovation projects for existing buildings to conform to new energy standards, through cost efficient, environmentally beneficial sustainable solutions.

**Pearl Rating System**

A brief description of the Pearl Rating System will be presented here. The system has the following components:

- Pearl Community Rating System
- Pearl Building Rating System
- Pearl Villa Rating System
- Temporary Pearl Building and Villa Program

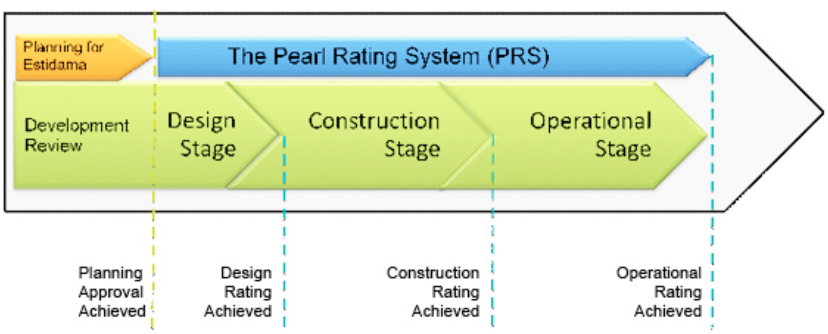


Figure 1: Planning for Estidama; Pearl Rating System, by the UPC, AbuDhabi (Estidama org., 2012)

**Pearl Community Rating System**

The aim of the Pearl Community Rating System (PCRS) is to promote the development of sustainable communities and improve quality of life. The PCRS encourages water, energy and waste minimization, local material use and aims to improve supply chains for sustainable and recycled materials and products.

The PCRS is applicable to developments that are multiple plot subdivisions, with a vehicular network and community facilities or amenities. A fundamental part of the PCRS is the requirement for master plan teams to develop Pearl Rating targets and guidelines for all buildings within the community.

The PCRS could also be used for large scale projects that do not exactly meet the eligibility requirements of the PCRS but want to incorporate sustainability principles into the project. Examples of these types of projects would be beach developments, parks and recreational areas that do not have permanent residential populations. For these projects it is recommended to use the applicable portions of the PCRS in conjunction with international best practices and obtaining agreement on the approach with the UPC.

The Community Rating System is designed to be used for development projects, which will support a minimum permanent residential population of 1,000 people, this being the minimum population for which community facilities are required to be provided in accordance with the UPC community facility requirements.

**Pearl Building Rating System**

The aim of the Pearl Building Rating System (PBRS) is to promote the development of sustainable buildings and improve quality of life. Achievement of a sustainable building requires the integration of the four pillars of Estidama together with a collaborative and inter-disciplinary approach to building development known as the Integrated Development Process. The PBRS encourages water, energy and waste minimization, local material use and aims to improve supply chains for sustainable and recycled materials and products.

The PBRS is applicable to all building typologies, their sites and associated facilities, including hospitals, warehouses, industrial buildings, laboratories and hotels. In essence, any building constructed for permanent use and that is air-conditioned must meet the PBRS requirements.

Within each credit, applicability and/or alternative specific requirements may be specified for the following building typologies:

- Office: applies to offices and associated spaces such as meeting rooms, reception/waiting areas, staff facilities, server rooms, corridors, toilets, print rooms, store rooms and plant rooms.
- Retail: applies to display and sale of goods, food retail (supermarkets, convenience stores), food preparation (restaurants, cafés, takeaways) and service providers (banks, post offices, travel agencies). This category also includes shopping centers, department stores and retail parks. It does not include isolated single use warehouse-type retail developments.
- Multi-Residential: applies to multi-family residential developments greater than three stories above grade. All villas must be assessed using the Pearl Villa Rating System (PVRS).
- School: applies to primary schools, secondary schools, sixth form colleges and further and higher education/vocational colleges and institutions.
- Mixed Use: applies to combinations of two or more of the above usage categories. Where relevant, individual credit calculations should be based on an area-weighted average.

All buildings intending to achieve a PBRS rating will be evaluated by the UPC. Nonetheless, the building must be registered with the appropriate Municipality and follow the building permit process.

**Pearl Villa Rating System**

The aim of the Pearl Villa Rating System (PVRS) is to promote the development of sustainable villas. Achievement of a sustainable villa requires the integration of the four pillars of Estidama together with a collaborative and inter-disciplinary approach to villa development known as the Integrated Development

Process. The PVRS encourages water, energy and waste minimization, local material use and aims to improve supply chains for sustainable and recycled materials and products. The PVRS respects the traditional 'fareej' residential design and supports historical priorities of solar shading, outdoor thermal comfort and internal privacy.

The Pearl Villa Rating System (PVRS) applies to any new stand-alone enclosed permanent structure to be built on a new or existing plot, and containing one dwelling unit for use by a single household, or a multi residential building of three or less stories above grade that houses multiple dwelling units.

A dwelling unit is one designed for residential occupancy with independent living facilities including provisions for sleeping, cooking and sanitation. The maximum size for a villa is 2,000 m2. Larger villas must comply with the Pearl Building Rating System. Villas built as temporary structures (planned to be in place for less than two years) are excluded.

Thousands of new villas will begin construction in the Emirate of Abu Dhabi and this system will improve the quality, comfort and sustainable performance of these villas.

**Temporary Pearl Building and Villa Program**

As of 26 May 2011, all new applications submitted to the municipalities for new, single, individually owned (one person) 1 Pearl villa or building will only have to meet the three revised Temporary Program Requirements listed below.

The exclusion only applies to villas and buildings that are owned by an individual and is not applicable to developers, conglomerates and business groups.

**Temporary Program Requirements**

| | |
|---|---|
| **PW-R1** Minimum Interior Water Use Reduction | » Only specifications for fittings, fixtures, and regulators are required |
| **RE-R1** Minimum Energy Performance | » Only the following U-Values must be met:<br>• External Wall: 0.57 W/m$^2$.K<br>• Roof: 0.31 W/m$^2$.K |
| **SM-R1** Hazardous Materials Elimination | » Requires an undertaking letter stating that Asbestos Containing Materials (ACMs) and Chromated Copper Arsenate (CCA) - treated timber shall not be used within the project |

**Calculators**

The applicable Water and U-Value Calculators are provided by the Estidama.:

- Villa Water Calculator (1 Pearl)
- Building U-Value Calculator (1 Pearl - Temporary)
- Villa U-Value Calculator (1 Pearl - Temporary)

**Conclusion: The Way Forward**

Unlike other sustainability frameworks Estidama is completely supported by the Abu Dhabi government. That means that when a project goes to tender, it requires the full support of the government to move forward, which allows approvers to examine and scrutinize aspects of the project before permits are granted.

Based on today's rating systems, once Estidama guidelines are met in a certain project, that project has the potential to give back to its environment, not just indirectly by saving energy consumption but by actually producing an energy surplus and putting energy back into the municipal grid. As an example, extensive use of PV cells is just the beginning.

Estidama has already been acknowledged as a framework that could work for the whole country, although not all Emirates have yet implemented Estidama-like strategies.

Gradual adoption of Estidama outside the Abu Dhabi has already begun. In the emirate of Al Ain, 'Plan Al Ain 2030' will incorporate one of the main pillars of Estidama in that it will require sustainable development on top of an existing master plan. This is especially important in Al Ain because it's known as the 'oasis' of the UAE and many people go there specifically for the climate and atmosphere.

Looking further, countries throughout the Gulf Coorperation Council (GCC) could potentially apply it as long as it is well planned and carefully implemented. The Abu Dhabi Urban Planning Council has declared it is implementing and carefully evaluating Estidama in Abu Dhabi specifically and then potentially other emirates and the GCC.

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# A METHODOLOGY TO QUANTIFY VISUAL QUALITY IN SMART COMMUNITIES: An optimization Approach

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## ABSTRACT

Creating green neighborhood developments yet remains a problem. Real estate developers in many of the developed countries work on providing smart complexes for new generations. Green thinking and resilience approach is started to spread more and widely applied due to the environmental and socioeconomic burden of livable communities. Green developments market is hampered by several factors one of which is the financing capabilities and the higher capital cost the owner will invest. The go-green decision has to be made during the pre-design phase where the feasibility and preliminary concept design are set for discussion. Development's profitability and pricing strategy are correlated as the latter reflects the property competitiveness hence potentially positions the developer in the market. The study proposes a spatial assistant tool for policy makers and local and private planning authorities to better plan and price for new green communities. The development of the model provides a methodological approach to quantify some aesthetic indices.

Keywords: *Competitive pricing strategy, genetic algorithms, sustainable development, LEED ND, visual impact and access to views indices,*

## INTRODUCTION

Throughout recent years, quality of life issues have become a crucial topic that alerts mid and high class tenants in neighborhood complexes in order to create viable communities and healthier societies. Over the course of the 20th century, the rapid increase in human population has raised the concerns about whether earth is experiencing overpopulation. A projected look into the future indicates population expansion which is accompanied with an increase in usage of resources hence creating threats to the ecosystem (Foley 2009) . A wide view over rural and developed communities depicts the clear picture of the contemporary urban design (DESA 2011). Negative environmental and social contributions of buildings consequently reflect the urgent necessity of having green sustainable communities and sustainable living. Sustainable communities are planned, built, or even modified to promote sustainable living in an innate carrying capacity, the so called the lifestyle. Sustainable living attempts to reduce an individual's or society's use of the Earth's natural resource and their own resources(C.E.L.L. 2011);(WCED 1987) working mainly on three pillars: society, environment and economy. Therefore, it can be explained as living within the. Thus we can recognize that living within green/sustainable communities, needs design and development decisions to be taken prior the execution or living within any of these complexes. Sustainable design practices encompass the development of appropriate technologies and sustainable living style which in return should match the growth and the desirable land use that carries the growth capacity(Wheeler and Beatley 2004).

Real estate developers need to create green communities while having a constructive pricing strategy for building and promoting these communities. Some aesthetic responsible factors of the high quality of visual environment in residential developments are not adequately considered or measured in neighborhoods' modeling and analysis. For instance, privacy, access to views and carrying land capacity indices take the least priorities in design considerations.

Leadership in energy and environmental design, LEED, is currently the most significant worldwide standard that is applied and analyzed to comply with the disparity of cultures and natures. LEED has a series of checklists and guidelines for different types of developments. In this study, LEED for Neighborhood Development is considered (USGBC 2010) and coupled with the developed pricing strategy of the proposed tool

The aim of the study is to quantify the cost of having high quality visual environment in neighborhood developments. The study addresses a set of issues:

1. The possibility of increasing the degree of what tenants see from inside their apartments (access to site premiums);
2. Reducing the degree tenants can be furtively peeped and watched by others through their apartments' windows (Visual impact).

The study aims at quantifying and optimizing aesthetic parameters in building new green communities and setting a pricing strategy for the sellable units. A spatial analysis evolutionary tool is proposed while associating LEED-ND standards. This model determines the carrying capacity of a residential land plot that maintains aesthetically pleasing environment with social and economic benefits.

**Train of thoughts**

The paper starts with (1) an introduction about visibility and urban design concept of green neighborhoods followed by (2) the proposed approach of measuring visual quality parameters (VQPs). Thirdly, (3) the quantification of visual quality using Ecotect commercial software is presented. This includes a questionnaire to examine and evaluate mid-class tenants' perception of some aesthetic parameters. Finally, (5) the paper ends by discussing the development of the proposed tool utilizing genetic algorithms approach. The study was conduced to a particular neighborhood; however, the paper provides a generic methodology that can be applied to other vicinities whilst changing some parameters. The study novelty is to provide a methodological approach of implementing sustainable urban planning concepts in neighborhood complexes design phase by considering natural resources (NR) and visual impact (VI) indices. This is coupled with genetic algorithms (GA) to find the optimal urbanization pattern in terms of land carrying capacity, location and orientation of dwelling units.

**Visibility**

Visibility is the state, or degree of being visible, without instrumental assistance, from the farthest point under given weather conditions (David A. Atchison 1 2004). A person sees though their cone of vision-COV which is the cone-shaped field of vision, normally about 60† that extends from the eye to the world beyond and the centreline of it is the cenral visual ray (CVR) (Encyclopedia,2011), figure (1). The visibilility range is the definition of the farthest point at which the eye can focus. This distance is measured to be 60 meters no more in the condition of clear vision within which a person can perceive a detailed picture of an object.

**Urban design**

Urban and pattern design standards are responsible for creating the identity, enhancing the economic and physical characteristics and planning decisions of the public realm of living complexes. The perception of complexes is defined by the pattern of natural resources, physical features, districts, clusters arrangements, greenery, special use areas, street patterns, and transportation corridors that spatially from the entire space. The visual spatial quality of a space is how the space characteristics have effects on each other whether positively or negatively. The more the urban pattern works on creating vitality and multiplicity of amenities in focal points with a less negative quality sceneries, the more it is developed, improved, and sustainable.

This is called the Visual Quality Parameter- VQP. VQP is defined by two parameters: (1) access to views and (2) visual privacy (1/visual impact), equation (1) where access to views is the inter-visibility of any living space and the favorable views such as natural resources (NR%), which are sometimes also referred to as 'site premiums' by real estate developers. And, visual privacy, 1/visual impact, is defined as the degree of inter-visibility between the openings of two spaces.

$$VQP = NR * \frac{1}{VI} \qquad (1)$$

A number of studies suggested that having access to views is highly desirable for tenants and employees in specific as it leads to increase productivity and general tenants' well-being, figure (2).

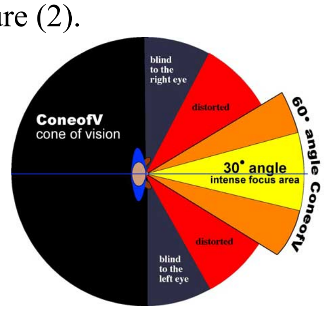


Figure 1: Cone of vision

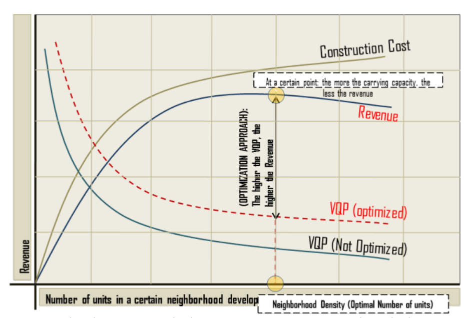


Figure 2: Correlation graph between VQP and pricing strategy

## VISUAL QUALITY MEASUREMENT

The world is witnessing the development of building performance analysis software. These tools help researchers and developers to study and analyze various phenomena within the developments. They are utilized mainly during the preliminary design phase to simulate different scenarios and variables. To perform this study, the way of measuring VQP was driven from Ecotect, one of the building performance analysis software (Autodesk 2011). In Ecotect, VI is measured by using line of sight technique. The main challenge in such measurement is how to spatially measure the impact on a three dimensional surface.

Initial trial was conducted by using Excel Microsoft Office where the calculations were done by using cone of vision. It was based on drawing the COV as a 2D triangle in plane x drawn from the center of the tested window of every unit and the intersection red areas are the actual visible areas, figure (3). The main drawback of this mean is the disability of analyzing 3D calculations. COV is measured by actual visible area seen in 2D plane while not considering the angle of incidence ( $\theta$ ) in calculation which is not real, figure (4). Ecotect utilizes the line-of-sight technique to measure VI. The VI is calculated between each of the dwelling units and all other units in the development (n-1) where n is the number of units. The cone of vision is drawn from the window that needs to be tested. As the below figures show, the bigger the incidence angle is (line of sight-2), the less visible area can be seen (visual impact is applied to the tested window).

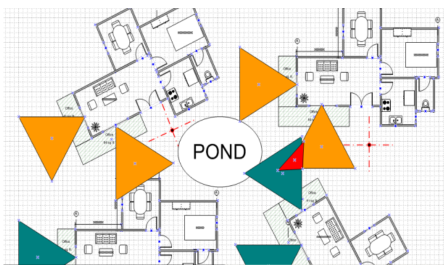



Figure 3: 2D Cone of vision

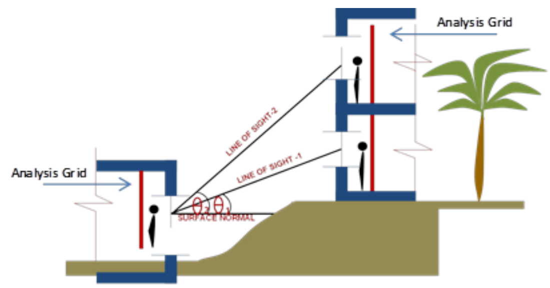



Figure 4: Line of sight in

## Study Approach

Measuring the visual quality within complexes is an existing application in Ecotect; however, different purposes and objectives. This study addresses a new set of data, which is the VI and NR. The VI is measured to determine the carrying capacity of the land and where to locate and orient the units within the layout; whereas, the NR is responsible for locating natural recourses and focal points in an optimal place that gets the highest degrees of visibility. These values are correlated with a pricing strategy for quantification. The pricing strategy is developed based on a questionnaire. This questionnaire tests the potential users' willingness of paying more to have better visual quality within the residential complex.

## Visual Impact

The measurement technique basically depends on the line-of-sight rays. From the tested window, a ray is drawn from each edge of it till the opposite edge of the adjacent window. The line is extended till it reaches the grid adjusted behind the windows figure (5). A virtual mesh (grid), within each of the dwelling units, is vertically located (1 meter behind the texted window).The grid is sub-divided into a series of sampled points. The line of sight from each side reaches the gird plotting 2D distances on each grid ($X_1$) and ($X_2$). Same procedure is applied vertically plotting 2D distances on each grid as well ($Y_1$) and ($Y_2$), figures (6 and 7).

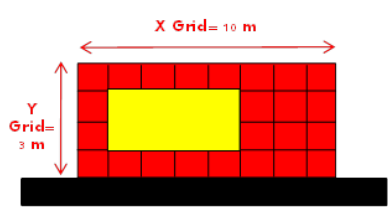
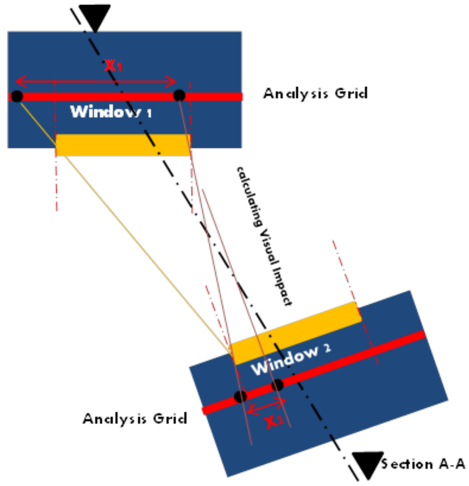



Figure 5: Analysis Grid




Figures 6: Lines of sight between 2units in the x axis

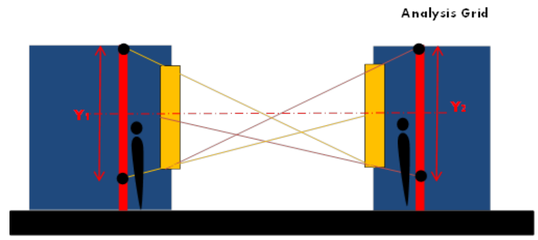



Figure 7: Section A-A

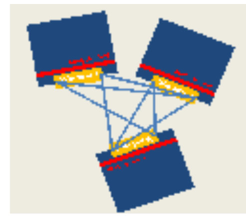


Figure 8: Summation

$X_1$ and $Y_1$ are multiplied to measure the internal square area seen via windows. The summation of $X_n$ and $Y_n$ distances is calculated in a data sheet figure (8) in units k and l as explained in the below equations.

$$VI = \sum_{i=1}^{n} \sum_{j=1}^{n} a_{i,j} \qquad i,j = 1,2,\dots n \quad \{a_{i,j}, i = j\} = 0 \qquad (2)$$

$$a_{i,j} = \frac{\sum_{k=1}^{m_i} \sum_{l=1}^{m_j} \left(\frac{b_{k,l} + b_{l,k}}{2}\right)}{m_i * m_j} \qquad (3)$$

$m_i$ = number of windows in unit i
$m_j$ = number of windows in unit j
$k = 1,2 \dots\dots m_i$
$l = 1,2 \dots\dots m_j$

$$b_{k,l} = \left(\frac{X_{k,l} Y_{k,l}}{A_l}\right) \qquad (4)$$

**Natural Resources**

In real estate terms, natural resources are a category of site premiums. They are usually classified as ‘Category A’, which includes golf course, lagoon, and public gardens. Tenants used to get concerned with the extent of seeing these premiums ($N_i$) and how close their units are located to them ($d_1$) as presented in figure (9).

## WEIGHTING VISUAL QUALITY

To quantify NR, structured interviews were conducted with a few of the top real estate developers in Egypt. The aim of these interviews was to know how real estate developers perceive the sites’ premiums in their pricing strategies. From the interviewees’ feedback, it was observed that there is not a constructive tool they use to measure visual quality; however, they generally classify NR as site premiums ‘Category A’ which has an impact of 25-32 % increase on the base cost of the unit.

Despondingly, measuring NR is indeed a pretty complex matter. From a mathematical point of view, the more the unit is away from the premium ($d_i$), the more the percentage of exposure it will be ($N_i$) which is not the real situation. Whereas, in measuring VI, the more the units are detached, the less visual impact value. Thus, to measure both indices, a function of the visibility range and distance should be applied. Distance $d_i$ is weighted based on the visibility range scale, which ranges from (0-60 meter). A graph is plotted to correlate the visibility range to the degree of visibility scale (from 0-1) as shown below figure (10).

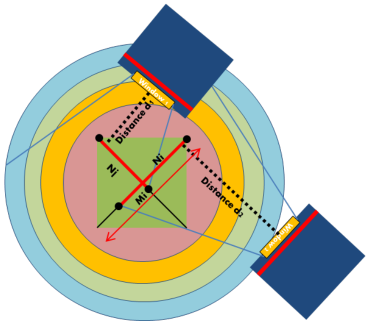


Figure 9: NR calculations

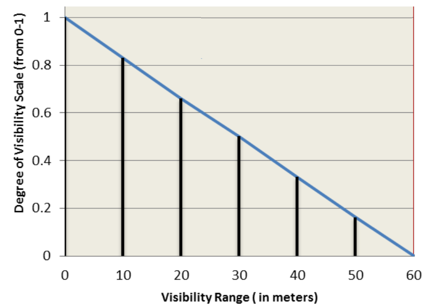


Figure 10: NR calculations

Syntactically, VI and NR percentages can be calculated as per the following equations.

$$V_i = \sum_{i=1}^{n} \left(\frac{L-di}{L}\right) x \frac{1}{P_i} \quad (5)$$

I: Scene number
N: number of respondents
L: Degree of Visibility
D: Distance (Visibility Range) 20, 40, 60 meter and beyond.
Pi: visibility analysis of each scene

$$NR = \left(\frac{Mi}{Ni} * di^{-1}\right) \quad (6)$$

$M_i$ = Overall distance of the NR
$N_i$ = actual visible distance of the NR
$d_i$ = shotest distance between unit i and the NR

## QUANTIFYING VISUAL QUALITY

The measurement explained above showed the math behind calculating VQ in the proposed tool. The technique is basically to employ cone of vision and line of sights between all tested units while considering the degree of visibility and distances between tested objects. The built-in calculations include also collision detection theorem which is applied to measure the NR percentage, explained later this paper.

To quantify VQ, a visual questionnaire is conducted to examine how the potential users quantify such parameter when they intend to buy new homes. Fifty potential users were asked to conduct the survey of one of the new settlements in New Cairo district in Egypt, which was selected for the study purposes. The neighborhood was modeled via using SketchUp (SketchUp 2012) and was analyzed by Ecotect. The 3D model was detailed up to LOD 3 (Kolbe, Groger et al. 2005) were the facades details were almost legible. Ecotect was employed to measure the VI providing the values in percentage, as shown in the very left column in table (1). Random scenes/shots were selected for the questionnaire. The selection has a particular criterion in terms of VQ; the senses vary between high and low visual qualities. For each selected shot, analysis was conducted and tabulated. Circles are drawn from the center line of the "tested object" with diameters of 20- 40- 60 and 80 meters as shown in figure (11). Table (1) gives detailed visual analysis for each texted window (ten scenes). VI was calculated than weighted based on the visibility range scale figure (10).

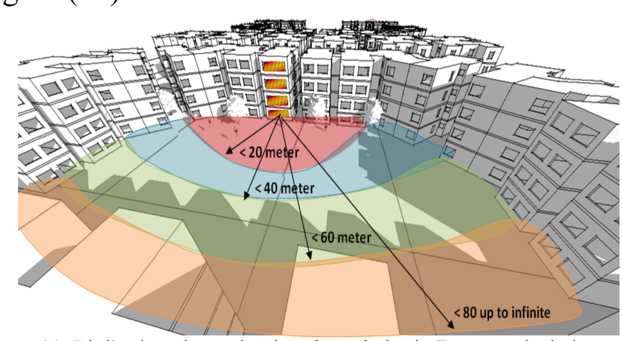


Figure 11: Bird's view shows the shots boundaries in Ecotect calculations

| | | Factors | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Views order | Visibility RANGE | Nearest Façade [in meter] | orientation of the nearest Facade | farthest Façade [in meter] | orientation of the far Facade | Actual Visible Area" ALL FACADES SURROUND" [in meter] | | AVA of all surrounding Reception Windows | AVA of all surrounding Reception Windows | AVA of all surrounding Reception Windows | AVA of all surrounding Reception Windows | Privacy % (1- Actual Visible Area ) |
| Worst to best | mazimum seen view by the tenant | | | | | AVA | # | Within 20 m AVA | Within 40 m AVA | Within 60 m AVA | Within 80 m AVA | Output |
| 10 | 40 | 20 | adjacent | 35 | shifted-adjacent | 101.58 | 9 facades | 24.96 | 13.63 | N/A | N/A | 62% |
| 9 | ≈70 | 9 | beside | 67 | adjacent | 466.16 | 8 facades | 9.4 | 70.42 | 92.13 | 0 | 63% |
| 8 | 92 | 10 | beside | 92 | shifted-adjacent | 272.73 | 6 facades | 0 | 9.02 | 24.83 | 37.91 | 74% |
| 7 | 62 | 21 | shifted-adjacent | 62 | shifted-adjacent | 47.87 | 3 facades | 5.93 | 4.29 | 0 | 0 | 79% |
| 6 | ≈100 | 10 | beside | 99 | shifted-adjacent | 728.35 | 9 facades | 0 | 0.95 | 50.49 | 76.03 | 82% |
| 5 | 90 | 20 | shifted-adjacent | 90 | around | 716.35 | 9 facades | 3.23 | 14.89 | 53.38 | 50.7 | 83% |
| 4 | 88 | 40 | beside | 88 | shifted-adjacent | 381.18 | 6 facedes | 0 | 0 | 50.16 | 6.21 | 85% |
| 3 | 92 | 18 | adjacent-perpendicular | 92 | adjacent | 115.71 | 5 facades | 1.32 | 3 | N/A | 5.76 | 91% |
| 2 | 41 | 12 | adjacent | ≈41 | shifted-adjacent | 246.12 | 2 facades | 9.23 | 2.69 | N/A | N/A | 95% |
| 1 | 92 | 10 | beside | 92 | adjacent | 952.04 | 6 facades | 20.97 | 2.39 | 3.46 | 1.97 | 97% |

Table 1: Visual Access percentage from ECOTECT visibility Analysis

## Questionnaire

The questionnaire contains 10 scenes starting with the best view and ending with the worst. The evaluation of scenes is based on privacy level and exposure of views. The respondents were asked to give an estimate price for each scene. To avoid biased feedback, cost margins were indicated for each scene as it is shown in the questionnaire template figure (12). The consecutive questions measure how tenants would pay extra money to have better orientation and location.

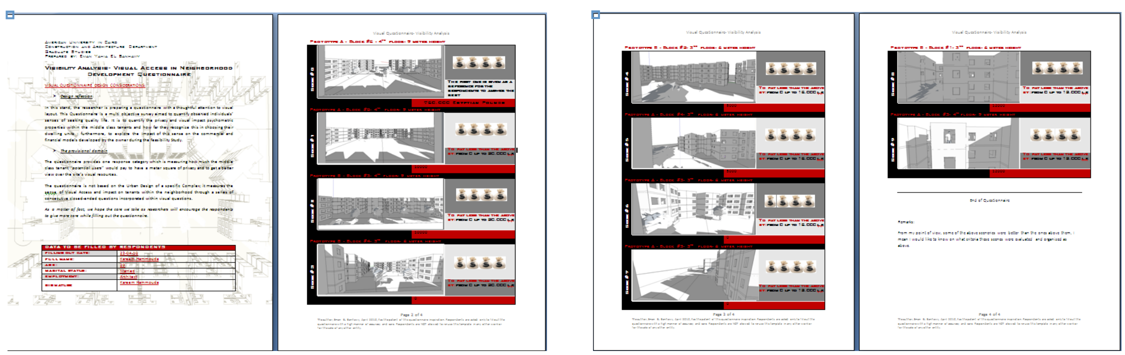


Figure 12: Visual Questionnaire

In all of questionnaire scenes, Ecotect visibility analysis technique was used to measure the VQ of each one. It is worth mentioning that in some cases, windows had a value of "zero" which means no visible area can be calculated. This happens when the two tested windows are above each other or beside each other where the angle of incidence is 180 degrees. This can be described in figure (4), the two units on the right side.

After getting the respondents' feedback regarding the pricing of the selected scenes, the VQ is calculated and weighted. It is a function of the visibility analysis of Ecotect, visibility range and distances between units. First, the summation of all visible area by each unit is divided by the overall exposure. Second, the visibility range scale is employed to relate the degree of visibility with the distance between the units hence weigh the VQ.

The visibility analysis values are calculated via Ecotect and tabulated in a separate sheet table (1), which shows all needed details of each scene. Questionnaire feedback was tabulated and average of prices indicated for each scene was also tabulated. Regression analysis is applied to formulate visual quality parameter (VQP).

**Simple Regression Analysis**

The hypothesized relationship is between the VQ and the premium paid for the units. As stated earlier the VQP is is a product of two: the value of the access to favorable views, NR, and the inverse value of the VI, equation (1).

The higher the NR and the lower VI values the higher the VQP and this formulation places equal weights for both values in this aggregated index. It is important to note that in general the NR and VI values will be strongly correlated and it is expected that a high covariance or a positive correlation coefficient that is close to one would exist between the two values in most cases. However, there may be some situations where this is not always true. For example a negative effect would be expected when obstructions veil the natural resource while at the same time the configuration exposes the space to neighbors. On the other hand, for a carefully designed space one would expect that the favorable views be visible and the same time exposure from neighbors would be kept to a minimum by use of shades, obstructions and landscape elements for example.

In any case, it is expected that the VI would strongly affect the selling price of the unit or the cost premiums that the buyers would be willing to pay. The main concept suggested here is that the higher the VQ index calculated the higher the premium that buyers would be willing to pay for the residential units. Therefore a simple regression was carried out figure (13).

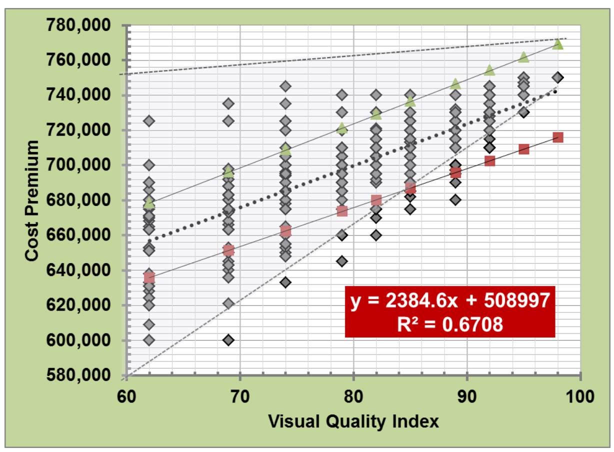



Figure 13: Pricing units and Visual Access Index trend

Where the dependent variable (y) is the cost of the unit to the buyer and the independent variable (x) is the VQ index (which is the product of NR and VI). The cost of the unit is equal to the base cost (which is the cost of the unit to the buyer including all other elements that affect the price, i.e. location, closeness to amenities and the story the unit is on). A linear regression was carried out and the least square regression line calculated is:

$$y = 2384.6x + 508997$$

It is important to note that the experiment presented here shows an approach for measuring VQP and its contribution to the price of the housing units. For each unit increases in the VQP, it has a direct proportional increase in cost premium. Accordingly, and by applying the formula, the next part of the paper discusses the logic and built-in algorithms of the proposed tool.

## TOOL LOGIC AND ALGORITHMS

The objective of developing the proposed tool is to optimize the location (X, Y) and Orientation (Θ) of a prototype and giving it the maximum access to views percentage (percentage of exposure (NR %)) and the minimum VI from other prototypes (maximizing the privacy index (VP %)). The cost impact of these two parameters (NR and VP) is reflected in the sustainable prototype-selling price, and overall development profit margin based on the conducted questionnaire.

**Evolutionary algorithms**

Evolutionary Algorithms (EAs) are inspired by the concepts of "natural selection" and "survival of the fittest" in the biological world. The math behind the EAs works as natural processes, such as selection, recombination, mutation, migration, locality and neighborhood. They work on the population of possible solutions (individuals) instead of iterating a single solution. GA is a method of solving optimization real-life problems (Elbanhawy, Sobeir et al. 2008). It repeatedly modifies a population of individual solutions by analyzing, evolving and changing a set of biological inspired operators that can change these individuals' behaviors or performance. At each step, the GA heuristically selects individuals from the current population to be parents, based on their "fitness" in solving the desired problem, and uses them to produce children of the next generations. Throughout iterations, the population evolves towards optimal solutions (Moler 2004). In this study, units' arrangement that gives high VI% and low NR % are neglected in each generation. These arrangements are called (least promising strings)(Moreira 1995). Giving the desired number of units (land carrying capacity), the tool should work on generating optimal solutions by applying GAs. The objective function is to optimize these units' prices hence the overall complex profit. Each unit contains 3 variables (X, Y, Θ); the number of variables is summation of (X, Y, Θ) of all units. The parents are selected from the individuals (number of units in development which ranges between (6-10 units/acre). These chromosomes can have up to (30 genes) which are (X1, Y1, Θ1), (X2, Y2, Θ2)…. (X10, Y10, Θ10). The developer decided to select 4 parents and start crossover process, figure (14) shows parents and population size in case of 10 units.

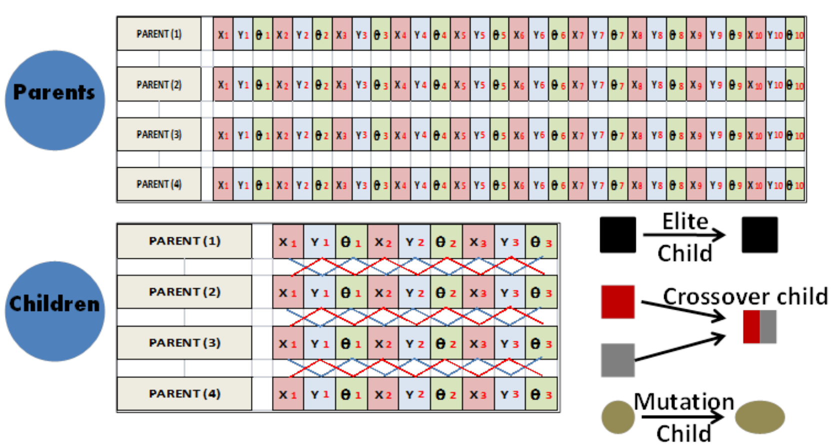



Figure 14: GA parents and population size ( incase of having 10 units/acre

In order to let the algorithms start running iterations, a validation criteria are given to start rejecting the bad generations / individuals to find the optimal solution. This criterion is related to the nature of the chromosomes (location, orientation, blockage, actual visible areas…etc.). It is the intermediate language between the developer and the program so that the tool can measure, run GA and ultimately shall generate results. The validation criteria include (1) the use of collision detection- separating axes theorem to reject overlapping units and regulate a constant margin between dwelling units which goes in line with zoning regulations.(2) Road network and amenities areas are excluded from this study as the tool assists to design residential areas ( buildable areas) layout.(3) The reception windows are the only type of windows that are being tested as the reception area is the highest interaction zone in the house in which tenants look for nice views to outside with less visual impact. Wet areas windows effect is neglected in the calculations. (4)Units and attraction and focal points design and shapes are neglected in VQ measurements. Square boundaries are drawn framing all elements as shown in figure (15).

Figure15: Square Boundries framing units and focal points in development

## ANALYSIS AND DISCUSSION

The questionnaire showed interesting results. When there was a scene for a-back-of-the-compound view with a high degree of privacy, it was weighted less than a view has a natural resource but has a higher degree of privacy. This shows that VI and NR are coupled indices. When calculating VI, the researcher can examine the privacy level as it was explicitly visualized in the questionnaire. However, it would be difficult to judge or test the natural resource exposure quantification due to the other parameters that cannot be neglected. In other word, to have a unit with a reception panoramic view over a natural resource won't exist without having other surrounding units with VI value which means less privacy.

The experiment here was for a single unit where all the independent variables affecting the cost of the unit to the buyer have been kept constant. In order to expand the model we suggest adding more independent variables and seeing if the relationship holds for units with different characteristics such as being on different floors for example. In this case we would only look at the price premium due to VQ and not the total cost to the buyer, which means that the basic cost would be different for the various points in our data.

## CONCLUSION

The world is in an urgent need of more green cities and smart communities (Beeton 2011). Planners and real estate developers are lacking constructive tools to assist in planning and pricing green communities. Some aesthetic parameters are not considered and incorporating such indices shall enhance the life cost cycle analysis LCCA of the development. LEED ND recommends having compact developments; whereas, having a medium density that better serves the communities. The tool facilitates design enhancement chances to sketch and design parking areas, biking racks, public storage areas and land entrance to have a compliant Neighborhood pattern that meets LEED ND rating system requirements and credits.

This study proposes a methodology to quantify visual quality parameters within neighborhood developments incorporating appropriate and competitive pricing strategy. Visual quality parameters address visibility analysis within neighborhoods and deal with privacy inside dwelling units and the access to outside views. Land carrying capacity, location of the units and focal points and the orientation of both are the key factors of the simulation. GA is employed to run different iterations till it reaches the optimal layout arrangement. The tool tends to try all possible what-if-scenarios and work on generating optimum layout and conceptual urban patterns where the (VI) is at the minimum and the (NR) is at the maximum.

Preferable solutions compromise between building healthier communities with high level of visual environment and maintaining a competitive pricing strategy that meets mid class tenants affordability and maintaining maximum revenue to owner (multi-objective function). The proposed tool was validated by being checked and tried by real estate consultants and developers. According to them, when the model was applied to real projects to ascertain its capabilities, it proved a high level of performance compared to actual results.

**Study limitation and future work**

It is worth mentioning that the questionnaire was conducted based on a specific context which is utilized to imply the relation (Y=aX+b) rather than giving constant coefficients (a and b) values to be used in all types of neighborhoods. This study presents a methodology for quantifying the VQP, which is not a factual equation to be generalized to all types of neighborhoods. This equation needs to be tested and the questionnaire needs to be examined in each time a researcher needs to quantify VQP for a certain type of neighborhoods.

In other words, although the actual numerical parameters in the regression model developed in this paper are specific to the local area of the study, the same technique can be applied easily to other areas with similar results. Moreover the same type of relationships between the identified variables will stand while considering different contexts such as timing, targeted sector, neighborhood class and type, location. It is important to note that a linear regression relationship may not always be the best type. For example, it is expected that in some cases where there are significant variations in the quality of the visual assets, the regression function may turn out to be non-linear

Finally, the proposed tool can be more beneficial and constructive as potential improvements to be applied. Future research is to include quantification and measurement of other indices for more green communities that include, but not limited to, water body conservation index, solar orientation, self-shading index, and right to light access index.

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# ARCHITECTURALLY EXPOSED STRUCTURAL STEEL: CLEAR COMMUNICATIONS FOR A BETTER PROJECT

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**Abstract**

AESS sits squarely at the juncture between architecture and engineering. Of the many structural materials used for larger, non-residential buildings, it is the one that requires the highest level of technical knowledge from the architect and the highest level of design appreciation from the engineer. The fabricator is often caught in the middle, attempting to create steel that is simultaneously correct for aesthetic and stability requirements. In some instances AESS can be priced out of a project because the finish expectations have been placed too high – for the budget or the type of project.

This paper will speak to new standards that have been developed by the Canadian Institute for Steel Construction (CISC) for the design and specification of AESS that are centered around a "Matrix" that classifies AESS according to factors that include visibility, fit, finish and form. The paper looks at design for constructability as this affects the ability of the fabricator/erector to deliver the project on time and on budget.

Also addressed will be issues arising from the recent influence of 3D modeling software on the generation of buildings that are more easily rendered than fabricated. This would include projects that use curved steel and non-rectilinear forms. New detailing software is discussed that greatly assists with bringing some highly challenging projects to reality.

**Keywords**

AESS, Construction communication, Steel construction, Steel detailing

## DEFINING AESS

Architecturally Exposed Structural Steel (AESS) is steel that must be designed to be both structurally sufficient to support the primary needs of the structure of the building, canopies, ancillary structures or pedestrian scale bridges, while at the same time be exposed to view, and therefore is a significant part of the architectural language of the building or structure. The design, detailing and finish requirements of AESS will typically exceed that of standard structural steel that is normally concealed by other finishes. AESS must be durable and maintainable. It must be able to resist corrosion if placed in a hostile environment and the design and finishes also resistant to urban pollution and general wear.[1] It calls for a different standard and style of detailing than standard structural steel.

AESS really only made its debut in North American architecture in the middle to late 1980s. The use of exposed steel grew out of the High Tech movement in England and parts of Europe during the 1970s and 80s. Much of the High Tech architecture of that period made use of highly elaborate structural steel systems that were based on modular construction, predominantly using the exposed steel as an exoskeleton. Most of the buildings had higher than normal budgets, crafting details that were not within the vision of Corporate North American clients. O'Hare International Airport in Chicago was the first Terminal to abandon expressive concrete in preference for steel. The detailing used by Murphy/Jahn was "between" the more elaborate High Tech details being used by Foster and Rogers and the use of expressed steel by Modernists such as Mies and Philip Johnson. The O'Hare structure was largely positioned on the interior of the envelope given the harshness of the climate, although it did express some steel on the exterior.

Hollow structural sections (HSS) only came into significant production in the late 1970s. They were immediately incorporated into High Tech buildings, and innovative connection design followed. The widespread use of HSS truly began to differentiate the exposed steel architecture of the late 70s and onward from that of the Modern Movement which had used a limited palette of wide flange, channel and angle type sections. Standard structural steel sections did not really lend themselves to expression in the newly expressed hinge and pin connections while HSS seemed well poised to encourage innovation in the same.

Fig. 1: Sainsbury Center by Foster (left) versus O'Hare International Airport by Murphy/Jahn (right). Sainsbury is rigorously modular where O'Hare begins to make more flexible use of a *family* of connection details.

## The Issues

Without any specifications for the design and detailing requirements for AESS, architects and engineers were left on their own to decide upon appropriate standards. These tended to polarize at either end of the scale – with the use of exposed steel in "big box stores" at the lower end and "Calatravesque" projects at the high end. High-end AESS tended to defer to "glove smooth finishes" that were achieved with considerable grinding and filling. Mid range projects that selected finish standards at the high-end could be and were priced out of existence. There was not a *differentiated standard* that could be referenced by the team. This state was exacerbated by the reality that traditional engineering and architecture education does virtually nothing to help prepare either engineers or architects to design AESS, concentrating instead on the design of standard (concealed) structural steel. Fabricators are either engineers by training or trained on the job through an apprenticeship system. If a fabricator has not worked on a variety of AESS projects the firm may not have a body of AESS work to reference, leading to additional confusion regarding project expectations.

With AESS, the architect, structural engineer and fabricator need to form a triangle of communication, which can positively impact connections, their design and cost. This interactive design process is very different from the more linear process associated with "standard" structural steel that is hidden from view where the architect steps back from involvement in the process. When AESS is used, the architect sees the exposed connections as part of the design expression of the project.[2] The working relationship becomes smoother over time when the parties gain experience on a range of AESS projects, but can be difficult if one party has less experience or does not have good information with which to make decisions.


Fig. 2: Consider the case of these two "tree" structures. The structure for Reagan International Airport (left) uses more standard section types to create a very tactile aesthetic while the support at the right uses pipe and castings that have been carefully fabricated to support a high gloss finish. Two unique specifications were required.

## Not All AESS Need be Created Equal

Decisions made in the design of Standard Structural Steel are very different from those required for AESS. The standard specification for structural steel also does not address the plethora of issues surrounding the detailing and erection of AESS. The bottom line is that not all AESS either needs to or should be fabricated to the same detailed requirements. Projects naturally vary by way of the use of the building, the distance to view of the steel, finish requirements (whether due to fire or corrosion protection), the desired aesthetic and the budget. More distant steel or that using a thicker intumescent coating would not benefit the expense of elaborate or finely finished details. Constricted sites can require innovation when it comes to erection – impacting the types of connections chosen.

There are primary factors that give rise to the differentiated Categories of AESS.

- **Connections mostly bolted or welded**
  (different aesthetics requiring differing levels of finish)
- **Tolerances required at fabrication and erection**
  (different as a function of scope and complexity)
- **Access to detail to perform required finish**
  (greater concern for workmanship may mean altering the detail or its location to allow access for different types of tools)
- **Degree of expression**
  (complexity of structure and connections)
- **Size and shape of structural elements**
  (W sections and HSS have different detailing requirements and their use infers a different approach to detailing and finish)
- **Interior or exterior setting**
  (weathering issues, need to fire protect, potential for impact damage)
- **Paint finish, corrosion resistance, fire protection**
  (depending on the relative thickness of the finish material, more or less care may be required when preparing the surface, edges and welding of the steel)

A set of documents was created by CISC: a specification for the engineers, an Appendix to the Code of Standard Practice for the fabricators, and an illustrated Guide for the architects that reflected the way the factors affected the “Form, Fit and Finish” requirements of the steel, and put the same into a language that was understandable by each discipline. A visual “matrix” was created that used language and terms that were common to all three documents and that acts as the central communication piece. (see Fig. 4) The specification and code focus on what you do TO prepare the steel and the guide elaborates on the impact of what you may put ON the steel.

Although the fabricators consulted were reluctant to commit, it was decided to include a range of cost premiums for the different categories of AESS as it was felt to be an important part of the decision making process, however approximate.

## THE AESS CATEGORIES

The initial point of technical reference is Standard Structural Steel (SSS) as defined in as it is already an established and well-understood as a baseline in construction specifications.

*AESS 1 – Basic Elements* is the first step above Standard Structural Steel. This type of application would be suitable for ordinary elements that require enhanced workmanship. This type of exposed structure could be found in roof trusses for arenas, warehouses, big box stores and canopies and should only require a low cost premium in the range of 20% to 60% due to the relatively large viewing distance as well as the lower profile nature of the architectural spaces in which it AESS 1 used. Surface preparation by commercial blast cleaning is the most important first requirement of all AESS, regardless of category.

*AESS 2 – Feature Elements* includes structure or "feature elements" that are intended to be viewed at a distance > 6m (18ft). This distance reflects the height of a high ceiling and is considered adequately out of visual range to appreciate finer finishes and also beyond touching. The process requires basically good fabrication practices with enhanced treatment of welds, connection and fabrication details, tighter tolerances for gaps, and copes. This type of AESS might be found in retail and architectural applications where a low to moderate cost premium in the range of 40% to 100% over the cost of Standard Structural Steel would be expected.

Fig. 3: The AESS Categories: (top left) AESS 1, (top right) AESS 2, (bottom left) AESS 3, bottom right (AESS 4). AESS 1 and 2 are located beyond 6 meters where AESS 3 and 4 are within view range and touch.

*AESS 3 – Feature Elements* includes structures that will be viewed at a distance ≤ 6m (18ft). The closer distance means that the viewer can see and potentially touch the steel. The Category would be suitable for "feature" elements where the designer is comfortable allowing the viewer to see the art of metalworking. The welds should be generally smooth but visible and some grind marks would be acceptable. Tolerances must be tighter than normal standards. As this structure is normally viewed closer than six meters it might also frequently be subject to touch by the public, therefore warranting a smoother and more uniform finish and appearance. This type of structure could be found in airports, shopping centers, pedestrian bridges, hospitals or lobbies and could be expected to incur a moderate cost premium that could range from 60% to 150% over Standard Structural Steel as a function of the complexity and level of final finish desired. This is the Category where grinding to remediate surfaces and welds is first included. Beyond taking the sharp edges off of all AESS1 and 2 steel, no grinding is permitted in those Categories. The elimination of unnecessary grinding was essentially the starting point of the Canadian AESS Committee discussions as it was negatively impacting the viability of projects.

*AESS 4 – Showcase Elements* or “dominant” elements is used where the designer intends that the form is the only feature showing in an element. All welds are ground and filled and edges are ground square and true. All surfaces are sanded and filled. Tolerances of these fabricated forms are more stringent, generally to half of standard tolerance for standard structural steel. All of the surfaces would be “glove” smooth. The cost premium of these elements would be high and could range from 100% to 250% over the cost of Standard Structural Steel – completely as a function of the nature of the details, complexity of construction and selected finishes.

*AESS C – Custom Elements* was created to allow for a custom selection of any of the Characteristics or attributes that were used to define the other Categories. It allows flexibility in the design of the steel, and therefore requires a high level of communication amongst the Architect, Engineer and Fabricator. The premium for this type of AESS could range from 20% to 250% over regular steel. A wide range may seem odd for “custom” elements, but the lower bound of this Category also includes specialty reused steel for sustainable purposes, and steel that might be purposefully less refined in its Characteristics.

**Table 1** - AESS Category Matrix

| Id | *Category* / *Characteristics* | AESS C<br>*Custom Elements* | AESS 4<br>*Showcase Elements* | AESS 3<br>*Feature Elements*<br>***Viewed at a Distance ≤ 6 m*** | AESS 2<br>*Feature Elements*<br>***Viewed at a Distance > 6 m*** | AESS 1<br>*Basic Elements* | SSS<br>*Standard Structural Steel*<br>CSA S16 |
|---|---|---|---|---|---|---|---|
| 1.1 | Surface preparation to SSPC-SP 6 | | √ | √ | √ | √ | |
| 1.2 | Sharp edges ground smooth | | √ | √ | √ | √ | |
| 1.3 | Continuous weld appearance | | √ | √ | √ | √ | |
| 1.4 | Standard structural bolts | | √ | √ | √ | √ | |
| 1.5 | Weld spatters removed | | √ | √ | √ | √ | |
| 2.1 | Visual Samples | | optional | optional | optional | | |
| 2.2 | One-half standard fabrication tolerances | | √ | √ | √ | | |
| 2.3 | Fabrication marks not apparent | | √ | √ | √ | | |
| 2.4 | Welds uniform and smooth | | √ | √ | √ | | |
| 3.1 | Mill marks removed | | √ | √ | | | |
| 3.2 | Butt and plug welds ground smooth and filled | | √ | √ | | | |
| 3.3 | HSS weld seam oriented for reduced visibility | | √ | √ | | | |
| 3.4 | Cross sectional abutting surface aligned | | √ | √ | | | |
| 3.5 | Joint gap tolerances minimized | | √ | √ | | | |
| 3.6 | All welded connections | | optional | optional | | | |
| 4.1 | HSS seam not apparent | | √ | | | | |
| 4.2 | Welds contoured and blended | | √ | | | | |
| 4.3 | Surfaces filled and sanded | | √ | | | | |
| 4.4 | Weld show-through minimized | | √ | | | | |
| C.1 | | | | | | | |
| C.2 | | | | | | | |
| C.3 | | | | | | | |
| C.4 | | | | | | | |
| C.5 | | | | | | | |
| | *Sample Use:* | Elements with special requirements | Showcase or dominant elements | Airports, shopping centres, hospitals, lobbies | Retail and architectural buildings viewed at a distance | Roof trusses for arenas, retail warehouses, canopies | |
| | *Estimated Cost Premium:* | Low to High (20-250%) | High (100-250%) | Moderate (60-150%) | Low to Moderate (40-100%) | Low (20-60%) | None 0% |

Fig. 4: The Matrix provides a systematic, additive approach to the relationship between the AESS Categories and their associated Characteristics.

The detailed Characteristics will not be addressed in this paper. The list is included in Figure 3. The Characteristics are additive, each AESS Category with increasingly stringent requirements. The intention of the list is to reflect the primary factors of influence, focus on the use and viewing distance, and remove requirements from the lower end categories that would be a waste of time and money to the project.

Worth noting is Characteristic 2.1, Visual Samples. These are common requirements for many projects when it comes to agreeing to specify finish materials and a potential problem for any AESS project as a full scale mock-up costs both time and money. Mock-ups are usually scrutinized very closely, at distances that are often much closer than in use. As the AESS in the project has become a critical element of the design and its finish is important, it is not surprising that architects and clients would like to see a sample prior to committing for the entire project. This characteristic highlights a variety of ways to satisfy this "need". It suggests alternate approaches that will save time and money. If a fabricator has experience in AESS other completed work can serve as the sample for the agreed nature of finishes. This can be accompanied by a 3D rendering showing how the particular details in question will be designed. Partial mock-ups of welded connections can be created to allow the architect and client to make a selection, without requiring the fabrication of a complete piece. In one instance where a very large unique element was required, it was actually incorporated into the final project although its finer details were different than the dozens of elements created for the project.

Fig. 4: The element at the left was the visual sample for the project. Given its size and expense, it was incorporated into the finished building. To find it on the right is akin to "Where's Waldo". Hence a cost and time saving that was worthwhile.

## CONNECTION DESIGN

Connections in AESS projects *become* the architecture. They not only have to keep the loads happy, but they have an extremely important aesthetic role. Once the category of AESS has been determined on the basis of the building use, distance to view, budget and finishes, the actual detailed design of the connections and member selection comes into play. It is easier to weld in the shop and bolt on site, although site welding is possible, with the proper provisions. Shop painting is also preferred, although this infers greater care in handling during transportation and erection. The team must agree on site remediation methods for damage as it is likely to happen, regardless of level of care.

When designing steel connections with aesthetics in mind, one of the major choices will be to bolt or weld. Bolting is less expensive and more often found in lower-end AESS.

Generally speaking you will see more bolted connections in AESS 1 and 2, and more welded connections in AESS 3 and 4. A high level of communication is necessary, based on the core ideas of the Matrix, when the team is trying to combine the aesthetic "parti" with engineering loading requirements and fabrication/erection concerns. Bolted connections may prove the easiest to negotiate as the decision to bolt already agrees on a "technical appearance". The actual arrangement and numbers of bolts and the method of bolting will be guided by the types of members chosen (tube vs. shapes).

If the desire is for an all-welded look, decisions will get more complex as the shipping limitations will come into play. Larger elements will need to be broken into smaller pieces for transportation purposes. The team needs to clearly understand the route from the fabrication shop to the site, bridge and road clearances and how much "police escort" is to be afforded. Discreet or hidden bolted connections can be used as an alternate to a fully welded solution. Again the AESS documents and visual references in the Guide will assist the team by providing some suggestions for consideration.

Fig 5: These two images show three variations in creating bolted connections that work in conjunction with welded members. The simple plates bolted to the ends of the square HSS on the right are less streamlined but the splice plates can be more discreet.

A companion web site has been created to assist students and practitioners in creatively undertaking AESS connection design. The web based resource is able to accommodate a wider range of images and projects than the print media of the Guide. The pedagogy behind the selection of material for the web resources is to develop connections based upon an understanding of basic connection principles and methods. http://www.architecture.uwaterloo.ca/faculty_projects/terri/SSEF1/

## CONSIDERATION FOR FINISHES

When making decisions about fabrication details for AESS projects, the final finish must be known from the outset of the project. Whether the finish is selected on the basis of fire protection or corrosion, it will greatly impact detailing. The nature of the final finish should assist in determining the types and treatment of connections. An intumescent coating with a fairly thick finish, or a galvanized protection system would preclude the need for fastidious grinding of welds and might suggest AESS 1 or AESS2. A high gloss finish would work best with AESS 4. AESS 3 projects might be able to work with a variety of finishes and details according to the way the connections are detailed. Referring to the projects in Figure 2, the more tectonic "tree" at the left is finished in medium gloss paint and the smooth "tree" on the right finished in high gloss paint. A reversal of these finishes would have been inappropriate and a waste of fabrication time spent on the "smooth tree" as considerable time was spent bringing the surfaces of the mechanical pipe and castings to a point where their natural orange peel-like finish would not show through the paint.

Finishes is an area that falls outside of the Standard Structural Steel specification and also the normal scope of work for the Engineer, beyond an understanding of basic fire and corrosion protection methods. The Architect will often work with a Fire Engineer when determining Code and Exiting issues, and in this ascertain the required ratings for assemblies and the nature of fire protection or suppression systems. When creating the AESS Specification and Appendix to the Code of Practice for the Fabricators, it did not legally make any sense to include finishes as these are covered in detail in their own specifications. It was decided to address the "impact of finish selection" on AESS as an expanded part of the Guide as it was to be highly illustrated and could assist by showing photographs of details using a variety of finishes. Again it is critical to communicate the choice of finishes among the members of the project team so that the impact of selection is clearly understood.

## FUTURE AESS: WORKING WITH COMPLEX GEOMETRIES

Improvements in the field of digital drawing over the last decade have radically improved the communication flow for projects and have also allowed for the inclusion of a wider range of complex geometries. Early High Tech projects such as the Sainsbury Center pictured in Figure 1 (left) made use of highly repetitive sections. Although the trusses were more complex than previous steel structures created from standard sections, some economy was achieved by the mass production of like elements – part of the theory behind the new architectural type. High Tech designs were typically based on repetitive geometries that relied on a simple linear expansion of modules/bays or an infinitely expandable grid, again using like elements. Although the buildings "looked" more complex than their Modernist counterparts and were more time consuming to fabricate, in reality the processes were akin to assembly line production in widespread use in other industries of the same period.

The development of BIM software has drastically changed what can be done in AESS designs. The software allows for an almost seamless flow of information from design through to detailing and shop drawings. The current detailing software can work with pretty well any 3D geometry that the Architect can invent. The 3D models created by the fabricator are able to form a visual basis for communication on the project. The connection details can be extracted as discussion items on joint design. Each structural member, truss or major connection can be extracted to form a shop drawing. Erection sequencing can also be extracted as separate 3D drawing sets.

Importantly the model can be used to drive CNC cutting equipment, enabling accurate cutting of complex shapes into plate material. Where multiple shapes of differing sizes are required to be cut from plate material, special "nesting software" is employed that will determine the least wasteful layout.

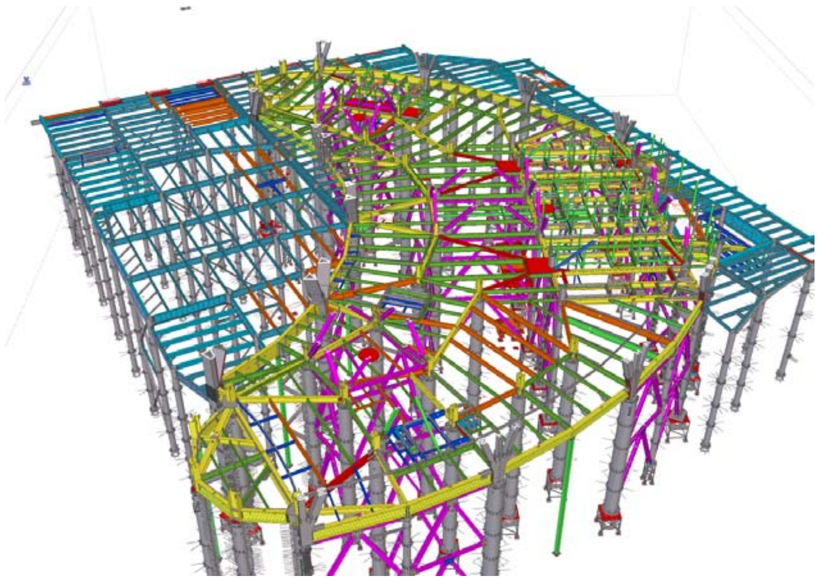

Fig. 6: This fabricator's drawing of the ground floor and basement framing of the Bow Encana Tower in Calgary, AB, Canada shows some of the complexity that can be handled easily by detailing software. Each connection is fully designed including bolting and welding information as responds to load calculations. The colors are indicative of function and construction sequence.[3]

The CISC suite of documents[4] was only fully released as of March 2011. Reports back of successes from the field are very positive and their use in projects is in part being driven by fabricator satisfaction. The flow on projects is smoother and discussions can focus on important details and issues and not on general levels of preparation. The suite has received International recognition and was revised for Australia and New Zealand and launched in November 2012. The construction industry has become a Global one, so this is viewed as very positive support for the CISC approach to the design and specification of AESS with an emphasis on improved communication for the team members.

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# MASONRY WALL FLASHING – CRITICAL TO PERFORMANCE, BUT OFTEN OVERLOOKED

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## ABSTRACT

In modern masonry wall construction, with the prevalence of cavity wall systems and decreased redundancy, the wall system's ability to manage water is more important than ever. It is impossible to keep a wall watertight without the installation of proper flashing. For a cavity wall to perform correctly, the flashings must have provisions to manage water and rapidly expel it back to the exterior of the wall assembly through weeps. Flashing must also be able to preclude unintended lateral movement of liquid water through the use of end dams. The installation of proper flashing can be achieved, at a small percentage of the overall design and construction cost, if the designer provides good details and the contractor understands how the flashing is intended to work. Too often flashing is installed poorly or omitted altogether, allowing excessive water into the wall assembly. This results in accelerated corrosion of embedded steel members, deterioration of the masonry assembly and an increased potential for mold growth. Remedially addressing these issues requires costly and disruptive repairs. Using lessons from the restoration of existing buildings, these problematic issues will be reviewed and several key flashing areas will be discussed; including copings, through-wall, parapet rain screens, window lintels and sills, rising walls, and shelf angles. Examples of incorrect flashing and the resulting damage will be used to show the role flashing plays in maintaining a properly functioning exterior wall assembly, as well as successful remediation of the same details.

## KEYWORDS

Coping, flashing, lintel, masonry, shelf angle, through-wall flashing, water management

## INTRODUCTION

Changes in building construction have increased the use and importance of flashing in maintaining the watertight integrity of exterior wall assemblies. As cavity walls gained popularity during the second half of the 20$^{th}$ century, there is a greater need for properly functioning flashing. Unfortunately, as we continue to repair cavity wall assemblies it has become clear that many designers and builders did not fully understand how to detail flashing and the crucial role it plays in a wall. There has been much improvement in construction since the turn of the century; however, there are still many modern buildings being constructed with improper and unworkable flashing details. The cost to install the flashing correctly while the masonry wall is being constructed is minor compared to the overall project cost; however, when the flashing needs to be repaired after building construction has been completed, it requires the costly and disruptive exercise of removing and relaying portions of the masonry veneer. Poorly installed flashing can cause additional deterioration to the building veneer and potential damage from water leakage at the interior. Pre-construction design for good flashing details and installation expenditure during construction of a building is a worth-while investment over the life of the building. Walls of all types, including modern cavity walls and historic mass masonry, have been found to benefit from flashing and water reduction.

## FLASHING

Cavity walls are constructed with an air space between a veneer and a back-up wall, and the veneer can consist of brick, stone, precast, etc. All of these materials, no matter how well constructed, will allow some amount of moisture penetration. The Brick Industry Associations Technical Note 7 "Water Penetration Resistance – Design and Detailing" indicates the intent of a cavity wall assembly is to contain the water that passes through the veneer in the air space (cavity) and quickly expel it to the exterior at the flashing locations. Based on experience evaluating and repairing failed building façades, we have found there are several *flashing principles* that are required for maximum effectiveness: 1) *Flash* – install continuous flashing to be watertight at all internal terminations, overlap and adequately seal at all lap joints, positively terminate to backup, and prevent unintended lateral water movement; 2) *Weep* – install adequate weeps to allow water to evacuate from the wall interior; 3) *Drip* - extend flashing beyond the exterior face of the veneer with a drip edge; 4) *Quality Materials* – utilize durable long-term materials; 5) *Skilled Craftsmanship* – use specialty personnel with expertise for installation.

Fig. 1. Poorly installed flashing exposed the steel angle to excessive moisture and allowed water to collect into the cores of the brick below.

If any one of these details is missing or not installed correctly, there is a high probability that water will bypass the flashing and remain in the wall (Fig.1). If the water that penetrates the veneer is not expelled to the exterior, the wall becomes susceptible to freeze-thaw damage and the potential for interior leakage. Steel embedded in the wall; lintels, shelf angles, structural members and masonry wall ties, will all corrode at increased rates with continual moisture exposure.

## FLASHING LOCATIONS

In standard cavity wall construction there are several primary architectural components discussed below, which need to be properly flashed to have the exterior wall function as intended. These components are the parapets, lintels and shelf angels, window sills, roof interfaces and building wall bases. These locations are typically more vulnerable to water infiltration and greatly benefit from flashing installation. In addition to this group of construction elements, there are always special circumstances that will require a creative combination of several flashing components to perform.

### Parapets

Parapets, the portions of the exterior wall that extend above the roof, are typically exposed to more extreme weather conditions than any other portion of the building. Parapet walls are also more susceptible to freeze-thaw damage because they tend to have a higher rate of moisture. Copings are the architectural components used to cover the tops of the parapets walls. Masonry copings are generally made of natural stone, cast stone, or terra cotta. Copings require through-wall flashing underneath to stop bulk rain water from entering the parapet wall below. Metal cap flashing can act as exposed through-wall flashing depending on the construction.

Characteristically copings come in pieces that range from 4 to 8 feet long. Mortar or sealant is installed at the joints between each of the pieces. These head joints are prone to premature failure due to thermal movement of the coping pieces and the extreme weather conditions to which they are exposed. Once the mortar or sealant fails, significant water infiltration through the joints can be expected. Through-wall flashing under the copings collects the water and directs it to the exterior; otherwise, the water would pour down into the middle of the parapet wall.

The through-wall flashing installed under the copings should consist of a durable material that will maintain a continuous watertight plane across the top of the parapet for a minimum of 30 years. Materials that will break down or become brittle should not be used. Drip edges must be used on both sides of the parapet so that any water which passes through the copings will be directed back to the exterior and cannot bypass the flashing. In some scenarios, a receiver and counterflashing can be used on the inboard side of the parapet to protect the termination of the roof flashing. Drip edges should be made of a metal that will not corrode, like stainless steel or copper. The flashing can be one continuous piece of metal or a self-adhered membrane can be stripped between the two drip edges (Fig.2).

Fig. 2. Good through-wall flashing will include drip edges on both sides and a continuous watertight plane across the width of the parapet.

Most copings contain support pins for anchorage. The support pins prevent the coping pieces from shifting or moving out of plane. It is imperative that the flashing cover these pins so they do not create a breach in the flashing. Thimbles (capped metal tubes soldered to a square metal plate) are often placed over the pins and tied into the flashing (Fig.3).

Fig. 3. Thimbles are often used to maintain watertight integrity at support pins.

All too often this critical detail is overlooked. Many copings do not have any flashing at all, or if flashing is present it does not extend out one or both sides of the parapet (Fig.4). It has become common to extend the roof flashing up the inboard side of the parapet wall and under the coping; however, the membrane is rarely extended out to the exterior face of the parapet. EPDM and plastic membranes are also very difficult to keep watertight around the support pins. Often sealant is used around the support pins in lieu of thimbles; however, sealant under these conditions will often have a reduced service life and will eventually fail and create an opening in the flashing that will allow water to pass.

Fig. 4. The lack of through-wall flashing below the coping allowed substantial water infiltration into the parapet, causing significant deterioration of the brick veneer.

The inboard side of the parapet needs to be protected from the weather; however, the parapet is integral in the evaporative drying process of the exterior walls. Rainscreen is an ideal way to both protect the parapet and allow the wall to breathe (Fig.5), because it is furred out from the bare masonry surface. Integration of the rainscreen with the coping flashing by extending the coping flashing out over the top of the rainscreen must be completed. The rainscreen must also have a provision to protect the roof flashing with counterflashing, but the counterflashing must be easily removable so when the roof needs to be replaced the entire rainscreen does not need to be removed. This is accomplished with an integrated two-piece receiver and counterflashing assembly.

Fig. 5. Rainscreens protect the parapet from the elements while allowing the wall to breathe.

Justin Henshell's article entitled "Don't Seal the Parapet" indicates direct applied membrane should not extend up the parapet wall more than the roof manufacturer's recommended flashing height, typically 8 inches. Roof membranes are often installed to cover the inboard side of the parapet to prevent water from bypassing the roof through the parapet. The membrane will protect the parapet but will also stifle the walls ability to dry through evaporation of the trapped moisture.

**Shelf Angles and Lintels**

Shelf angles support the veneer, typically at the floor lines, while lintels support the veneer at the openings above windows and doors. They both create horizontal breaks in the cavity. For the wall to perform properly, the flashings at the shelf angles and lintels must have provisions to manage water and rapidly expel it back to the exterior of the wall assembly. This requires the following flashing details; the flashing has to be well terminated to the backup wall in the cavity so that no water can bypass; a drip edge must be used to ensure the water that runs off the flashing is expelled beyond the exterior face of the veneer and cannot run back under the flashing, the laps in the flashing must be overlapped and sealed tight, and end dams must be used at all discontinuous angle locations to limit lateral water transmission (Fig.6).

Fig. 6. Good shelf angle flashing requires the use of a drip edge and be properly terminated in the cavity (termination bar and sealant here).

Corrosion effects metal components, particularly where embedded and in direct contact with adjacent material (brick, stone, mortar, etc.). With water and oxygen, steel will corrode and expand with high pressure and volume created by the exfoliating rust layers (Fig.7). The corroded steel combined with rust will occupy a larger volume of space than the original steel alone, and impart expansive stresses on surrounding materials. Appropriately installed flashing protects the steel at shelf angles and lintels from exposure to moisture, greatly reducing the rate of corrosion and the potential for severe damage.

Fig. 7. Poor flashing details allowed water to continuously reach the steel angle, rapidly increasing the rate of corrosion of the steel.

It is still commonplace to install sealant along the front edge of a shelf angle or lintel. The thought is that the weeps will allow the water to exit while the sealant will keep the bulk rain water out. The problem is that weeps often become clogged, particularly weep tubes, and the sealant traps the water in the system (Fig. 8). Since the flashing does not extend beyond the face of the masonry face, water trapped in the system will bypass the flashing and sit on the angle, continue down inside the cavity wall or enter the interior of the building. Open head joints are a good option for weeps, spaced a minimum of 24 inches apart, filled with cell vents or weep vents installed to prevent clogging. Sealant may be installed underneath the drip edge to prevent wind driven rain from getting under the flashing, but should not be installed at the flashing front edge where water is being expelled. The bed joint at the flashing line should always be mortar since mortar can breathe and will allow trapped water to escape.

Fig. 8. Clogged weep tube keeps water trapped in the wall.

**Window Sills**

Window sills are notorious for allowing water into the exterior wall assembly. Window systems tend to act as their own separate cavity systems, collecting water internally and directing it to the exterior through weeps at the bottom of the window frame. Without good sub-sill flashing underneath the window system, this water can often work back into the cavity wall assembly (Fig.9). Sills are also susceptible to water infiltration because often they project out from the building and are exposed to the rain water that runs downs the window glass. Water penetration at the window sills can often cause severe deterioration of the masonry below.

Flashing at the window sill can be directly below the window such that the window system sits on the flashing or contained within the sill masonry directly below as sub-sill flashing. Window sill flashing

Fig. 9. Severely deteriorated masonry due to water infiltration at an improperly flashed window sill.

should turn up behind the window system so that it captures the water that dumps out from the window weeps and does not allow the water to run off the inner-side. The flashing must be extended out to daylight and should not be sealed closed (Fig.10). Unfortunately, in an attempt to correct leaks at certain window assemblies, the weep system between the flashing and the window frame is often sealed closed because it's misdiagnosed as a water infiltration source. Sealing the flashing can also seal the weeps of the window system, actually increasing the amount of water infiltration.

Fig. 10. Window sill flashing should extend out to daylight and must not be sealed closed so water is allowed to escape from the window frame weeps (picture at right).

**Roof Interface**

Where a roof interfaces with a rising wall it is crucial to have sufficient flashing or it is almost a given there will be interior water leakage. Any water that is traveling down the cavity that is not directed out to the exterior by the roof interface flashing will continue down the cavity and end up in the interior of the building. The roof interface flashing needs to be positively terminated to the backup wall in the cavity (Fig.11). This can be done with either a termination bar and sealant or by extending the flashing into a bed joint of the back-up wall. The flashing must extend out to daylight and typically incorporates a receiver and counterflashing to cover and protect the roof flashing.


Fig. 11. Good roof interface flashing is properly terminated in the cavity and extends out beyond the face of the veneer.

Where the building wall interfaces with a sloped roof, step flashing should be used. Step flashing can be either regleted into the wall for mass masonry or installed as step pans into a cavity wall system (Fig.12). The installation of good end dams is crucial for the step pan flashing to function as intended, since it is capturing a given tributary area of potential water infiltration.

Fig. 12. Proper step flashing has good end dams and extends out to the exterior.

It is typical for the roofer to be responsible for installing the roof interface flashing, especially when the lower roof is an addition to the main structure. Since the roofer is focused on protecting the roof flashing, the roof interface flashing tends to consist of a counterflashing that only extends one or two inches into the bed joint of the veneer. This protects the roof flashing termination but does nothing stop the flow of water down the cavity (Fig.13). It is imperative that at all roof interface locations have through-wall flashing installed.

Fig. 13. Poorly installed roof interface flashing almost always leads to interior water leakage.

**Base Building**

Since the cavity of a cavity wall assembly continues all the way down to the base of the building, it is important to have good water management at the bottom of the wall. Base building flashing will expel the water to the exterior just above grade so the water will run off away from the building. Without flashing the water would continue down the cavity and potentially infiltrate the masonry, structure, or possibly the building interior (Fig.14). Water could also get trapped in the cavity and cause potential freeze-thaw issues with the masonry. Flashing principles should be followed by terminating the through-wall flashing at the backup and weeping the water back to the exterior.

Fig. 14. Without through-wall flashing at the base of the building, water will remain in the wall system.

Fig. 15. An example of proper through-wall flashing.

## CONCLUSION

Proper flashing is imperative to maintaining a watertight exterior wall assembly. Peer education from experienced professionals within the industry and collegiate educational programs are paramount for these concepts to succeed. A crucial element is that the cause of the water infiltration must be understood before a repair can be implemented to ensure success. This can be achieved when the designer and contractor follow the basic principles of flashing, some which can be directly applied and some requiring more creative detailing. Improper flashing details are still being issued on construction documents and contractors that do not understand how flashing is intended to work are still improperly installing flashing. Experience when specifying flashing is important, as costs are highly variable, depending on the building, constriction, access, and wall condition. Finer detailing and materials in masonry construction has seen innovation over time, but the base concepts remain relatively unchanged – with the same applying to flashing. The key concept is getting the fundamental flashing concepts correct and building performance will follow. The cost difference between well installed flashing and improper flashing is relatively small; but the difference in how the building wall will perform could be exceptional.

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# Advancing the Structural Use of Earth-based Bricks: Assessing the Reliability of Existing Testing Procedures

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**Abstract**
Standards and codes can play a key role the social acceptability of earthen masonry. This notwithstanding, the existing regulatory framework for earth-based masonry construction is limited to derivatives of performance standards and codes that were developed for concrete masonry units. The discussion in this paper presented work directed at contributing the development of a reliable resting regime for interlocking bricks. The different testing regimes investigated include crushing full sized blocks (horizontally), 2 inch and 1.18 inch cubes and units with filled recesses testing in compliance with the provisions of ASTM C140-12, Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units. The findings have revealed that the numbers obtained for compressive strength change depending on the testing regime. In additional, the recorded values for compressive strengths were much higher when the samples were tested based on the provisions of ASTM C140-12, Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units. As this procedure accounts for the unit geometric properties of the interlocking block, the results suggest that it is a more reliable testing regime.

**Keywords:** Earth-based bricks, Regulatory Framework, Testing

## INTRODUCTION

Building materials can be classified rated as best for the environment if they contain the following characteristics: (1) materials made with salvaged, recycled, or agricultural waste content; (2) materials that conserve natural resources; (3) materials that avoid toxic or other emissions; (4) materials that save energy or water; (5) materials that contribute to a safe, healthy, built environment [5]. There has been a specific concern over greenhouse gases (GHGs) that has resulted in several efforts being directed towards reducing their release into the atmosphere. In Condition 2 of LP Hedelberg's movement, The Natural Step, there is a caution against the use of man-made materials that take a long time to decompose where dioxins are explicitly identified as examples of compounds that will almost never be broken down by nature. Given that building materials are largely inert, key areas of concern from an ecological perspective are ensuring that the manufacturing is done with the least impact and also designing the products for easy disassembly and recycling (Kibert, 2005). An assessment based on an ecological perspective makes earth-based building materials good options to explore as a way of minimizing the adverse effects of buildings on the environment.

However, it is important to bear in mind that ecological concerns comprise just one aspect of greening the built environment. The definition of what would constitute a sustainable building system is much broader. For the discussion in this paper, the authors have linked the performance goals to the efforts directed at delivering "high performance building" systems. In 2008, the US building enclosure community launched a formal initiative directed at delivering high-performance buildings. This initiative underscored the linkages between energy efficiency, durability and the quality of the indoor environment (Bomberg and Onysko, 2009). A "high performance building" here refers to the Energy Policy Act of 2005 (EPA, 2009) description of: "a building that integrates and optimizes all major high performance building attributes, including energy efficiency, durability, life cycle performance, and occupant productivity." Clearly, optimizing the structural performance of building materials constitutes a key aspect of realizing a high performance building. The authors have been assessing the potential for using earth-based bricks in high performance building units.

The use of earth-based technologies has been greatly limited by concerns of their physio-mechanical properties (Lazurus, 2005; Scrivener, 2004). Consequently, there are restrictions on their use. For example, in the New Mexico Building code Section 12.7.4.23 which governs the use of Compressed Earth Block Construction, a general clause "A" forbids their use in any building more than 2 stories in height. Compressed bricks are also less durable than conventional building materials (Lazarus, 2005, Obonyo, 2010). In the recent years stabilizers, such as cement, are added to the soil to improve the physio-mechanical properties of the resulting wall. Despites these developments, the use of low cost, labor intensive and energy efficient traditional building materials and techniques such as compressed bricks remains problematic with many professional expressing concerns over their structural use (Obonyo et al, 2010).

The authors have been doing work directed at advancing the structural use of earth-based bricks. One of the issues that has emerged is a key impediment is the lack of universal accepted codes and standards. In addition to setting the performance targets, universally codes and standards will with establishing confidence in the material. During a comprehensive literature review the authors identified some testing procedures that are derivatives of the ones commonly used for concrete masonry blocks. These procedures use samples that are of different shapes and sizes. The discussion in this paper is based on work that was done to quantify the differences in results that can be attributed to the aspect ratio of the samples used during the testing.

## METHODOLOGY

CSEBs (Compressed Earth Bricks) were manufactured with locally obtained soil, type I/II ordinary Portland cement, and dried coconut fiber/sisal fiber. Another set of blocks; without any reinforcement was also manufactured for control purposes. Both sets of natural fiber were cut into lengths of approximately 0.4 inches. The length of 0.4 inches for the coconut was selected based on experience from a previous project, where 0.4 inch length coconut fibers were found to make the matrix and ensured that strands of fiber were not sticking out of the surface of cured blocks. The length of the sisal fiber was kept at 0.4 inches to enable comparison of test results with the results from the blocks reinforced with coconut fiber. A grain size distribution test was run on a sample of the soil used to produce the blocks at the Florida Department of Transportation's materials lab in Gainesville using the American Association of State Highway and Transportation Officials (AASHTO) soil classification system M 145/ ASTM D3282. A liquid limit of 33% was recorded for the soil sample using ASTM D4318 as the testing standard. The soil was classified as sandy based on the results of the grain size distribution test. The soil was kept outdoors at the production site and covered with tarp.

Batches of soil, of weight 100lbs was prepared to produce a total of five blocks. Based on the size of the mixing tub used, 100lbs of soil was determined to be the maximum weight of soil that the tub could contain and still achieve a thorough mix (See Table 1). The mix in the tub produced a total of 5 CSEBs. The initial set of blocks started with 5% cement by weight (Adam, 2001; Rigassi, 1995). Producing two batches simultaneously provided adequate time to finish pressing the blocks without excessive retention time. The procedure also ensured that the hydraulic pump running the block press wasn't running idle between mixes. All materials were weighed dry.

**Table 1: Mixing Proportions by Weight (lbs)**

| Block | Soil | Cement | Coconut Fiber | Sisal Fiber |
|---|---|---|---|---|
| Soil Cement Coconut Fiber | 100 | 8 | 1.6 | 0 |
| Soil Cement Sisal Fiber | 100 | 8 | 0 | 1.6 |
| Soil Cement | 100 | 8 | 0 | 0 |

The dry sand and cement were weighed and placed in a large mixing tub. This was thoroughly mixed using shovels and hand trowels to get a uniform mix. With the batches that included the coconut and sisal fibers, the fibers were introduced gradually into the dry mix as the mixing process went on. The dry mix was then watered gradually in a uniform manner without halting the mixing process. Previous blocks manufactured using a similar soil type established a target moisture content to yield best results. The "drop test" (UNCHS-HABITAT 1992), was used together with the target moisture content to determine the amount of water to be added to each batch. The quantity of water added varied with each batch. The variation could have been a result of the soil kept outside absorbing some moisture from the atmosphere. The soil however looked dry upon visual inspection. The soil-cement coconut/sisal fiber batches were mixed until the mix was homogeneous and satisfied the drop test. The process was repeated for the control batch.

Once the soil-cement and soil-cement fiber batches had satisfied the drop test and visual inspection requirements, the batches were fed into the hydraulic press. The press is designed to compress the soil mixture from both the top and bottom of the mould. Both top and bottom presses were engaged for a minimum of 3 seconds consecutively, exerting a maximum pressure of 1000psi each time. The compressed blocks were then ejected from the mould and carefully moved and placed on pallets outdoors. The resulting CBEB units were of the Interlocking genre (see Figure 2).

Figure 2: Brick Production and the Resulting Interlocking Brick

The interlocking blocks were covered with a tarp after placing and watered the next day. The blocks were stacked after two days but still kept under a tarp and watered daily for a minimum of seven days. The initial curing done during the first two days was to minimize the occurrence of cracks and the breaking off of pieces of the block during stacking (Bland, 2011).

## RESULTS AND DISCUSSION

Because of the geometry of the bricks, tested the compressive strength of the interlocking blocks using different procedures based findings from a comprehensive literature review to identify the most reliable testing the regime. These have been described in the subsequent paragraphs. A Forney FX 250/300 compression test machine was used in testing. Table 2 summarizes the results for the first two procedures: Full sized blocks (horizontally) and cubes cut from blocks (2 inch and 1.18 inch cubes).

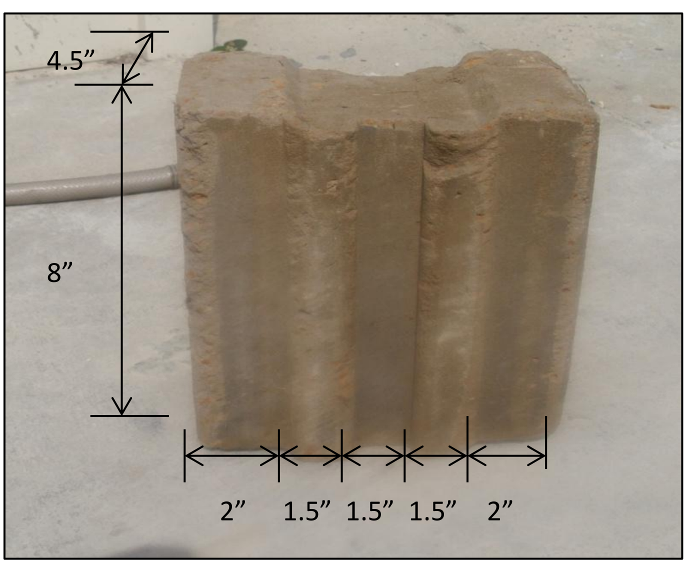

**Figure 3: The Geometry of the Interlocking Blocks**

1) ***Test blocks in the horizontal position:*** This test set-up was similar to that employed by Mesbah et al, (2004) when trying to direct testing the tensile strength of CSEBs. Failure of the blocks was initiated at the mid-section (web) which represented the smallest cross-sectional area of the blocks during testing. The shape of the blocks and orientation of testing indicated that stresses were concentrated in the lowest cross- section where failure was initiated. This suggests that the results obtained under these conditions cannot be said to be representative of the entire block. During testing, the compression load continued to increase even after initial cracking was observed. The authors attribute this to the presence of the fiber. They will verify this through testing unreinforced CSEBs using the same procedure.

2) ***Cutting cubes from blocks for testing:*** Cubes of size 1.18" (Azeez et al, 2011) and 2" were tested. The 2" cubes were tested per ASTM C109 and compared with the results obtained from the 1.18" cubes. It was observed that at the same OPC and coconut fiber content, compressive strength values varied with the size of cube specimen tested. Both sets of cubes were cut from the same block. The 1.18" cubes yielded compressive strength results lower than the 2" cubes. The values for both sets of cubes were much lower than those obtained when the full sized bricks were tested (Procedure 1).

3) ***Filling recesses with appropriate strength mortar/plaster for testing:*** Recesses of the blocks were filled with gypsum plaster and blocks capped with a thin layer of gypsum plaster for testing (Figures 9 and 10). Typically, cracks formed before peak load was reached during testing. Some blocks spalled at the edges but this was not observed for all tested specimen. All blocks however had visible cracks. With specimen that spalled, it occurred at only one edge. Material from the spalled edges did not fall off but appeared to be held in place by the coconut fiber. This behavior will be further studied through investigating the failure of unreinforced CSEBs.

The test set up and procedure using for the an additional set of samples was based on the provisions of ASTM C140-12, Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units. Protrusions on the blocks were dry cut with a wet tile saw and sanded down. Approximately 0.5 inches of block material was cut off from each block [Figure 4: (a)]. The recesses of the blocks were filled with gypsum plaster as shown in [Figure 4: (b) and (c)] after which they were capped with a thin layer of gypsum plaster to create an even surface and facilitate uniform transfer of stress between platens and specimens [Figure 4: (d)]. This was also to reduce friction between the platen and specimen. The average block sizes of tested specimen were approximately 8.5" X 8" and 4.5" thick.

**Table 2: Compressive Test Results (PSI) for Coconut fiber reinforced CSEBs**

| | Full Sized - Horizontal | 2” Cubes | 1.18”Cubes |
|---|---|---|---|
| | 265<br>263<br>330<br>385<br>310 | 275<br>311<br>300<br>325<br>239 | 250<br>235<br>301<br>298<br>285 |
| Mean | 311 | 290 | 274 |
| Standard Deviation | 50.6 | 33.9 | 29.7 |

The gypsum capped blocks samples were crushed using a Test Mark compression testing machine CM-500 series with a maximum compression capacity of 2,224KN and a spherically seated upper plate. The upper bearing plate was used to ensure that the surface area of tested samples was adequately covered. Failure was typically characterized by cracks alone and/or cracks with spalling at the edges of blocks [Figure 4]. The values obtained have been summarized in Table 4. Clearly these numbers are much higher than the ones obtained using the other procedures. Based on the higher level of compaction that has been achieved through using a hydraulically operated press machine, the authors believe the numbers derived using this final procedure are more reliable suggesting that this could be more accurate testing regime. This being further investigated in on-going efforts and will be reported in a future publication.

**Table 4: Compressive Test Results (Gypsum Capped Blocks) @day 67**

| Soil- cement- coconut fiber blocks | Compressive strength (psi) |
|---|---|
| #1 | 878.76 |
| #2 | 729.57 |
| #3 | 764.33 |
| #4 | 827.00 |
| #5 | 762.311 |
| #6 | 794.97 |
| **Mean** | **792.82** |
| **Standard deviation** | **53.48** |

(a)  (b) 

(c)  (d) 

**Figure 4: Sample Preparation a) Sawing off the Edges; b) and c) Filling up the recesses; d) Capping**

**Figure 5: The Test Set Up and the Spalling**

## CONCLUSION AND FURTHER WORK

In Obonyo et al (2010), the authors reported on the deliberations from an NSF US Tanzania workshop in which participants identified the key barriers to the widespread adoption earth-based bricks. Quality control issues and the lack of a regulatory framework featured prominently in the workshop deliberations. The authors have established through conducting a comprehensive literature review that the existing regulatory framework is limited to derivatives of performance standards and codes that were developed for concrete masonry units. It will be difficult to fully address the existing concerns over the structural use of earth-based bricks without having a reliable way of accurately assessing their performance. Many of the proponents of the technology are deploying for use in low income communities where a lot of masonry testing is limited to quantifying the units' performance using compressive strength properties.

Some of the commonly used testing procedures appear to ignore the impact of the aspect ratio. From the results in the preceding section, it is actually possible that some of the existing performance-related concerns may be attributed to the actual properties being grossly underestimated during testing. Cubes are much lower than the ones obtained when samples were tested based on the provisions of ASTM C140-12, Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units. The authors are undertaking further work to validate their position that the values obtained using the provision of ASTM C140-12 is more reliable. Many of the existing testing procedures also downplay the impact of the geometry of the blocks. CBEBs are often used as interlocking blocks to either to further reduce costs through deploying mortarless walling elements or for enhancing resistance to lateral loads due to, for example, wind and earthquake. Further work needs to be done to assess the best testing regime for the existing geometric configurations. The authors are currently doing work directed at doing just that. The findings will be reported in a future publication.

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# DEVELOPMENT OF KINEMATIC EQUATIONS FOR RACKING PERFORMANCE EVALUATION OF FOUR-SIDED STRUCTURAL SEALANT GLAZING CURTAIN WALL SYSTEMS

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## ABSTRACT

Full-scale, "unitized", four-sided structural sealant glazing (4SSG) curtain wall system mockups featuring a re-entrant corner were subjected to cyclic racking displacements in accordance with the American Architectural Manufacturers Association AAMA 501.6 protocol to determine serviceability and ultimate behavior responses. Sealant cohesive failure and glass cracking were identified as limit states and corresponding drift levels were determined. The geometry of the mockup was used to develop equations that predicted the displacements of the glass, relative to the frame, based on the independent variable of inter-story drift. The displacements from those equations were then related to the effective shear strain of the structural silicone and the drift capacity of the system. This paper describes the concepts and results of the kinematic equations developed.

## KEYWORDS

Curtain Wall, Glazing, Dynamic Racking, Kinematic Equations, Structural Sealant Glazing

## INTRODUCTION

Prediction of seismic behavior of "unitized" four-sided structural sealant glazing (4SSG) systems currently requires full-scale mockup testing. In order to reduce the need for such tests, development of prediction equations are necessary. The intent of these equations is to serve as design aids for 4SSG curtain wall systems and to avoid a trial and error design method. This is significant since the AAMA 501.6 testing process takes time and consumes resources. This paper presents the development of such kinematic equations derived from racking tests of a full-scale mockup with a re-entrant corner.

There have been several recent studies at The Pennsylvania State University on curtain wall seismic performance (Memari et al. 2006, 2007, 2011, and 2012a, and 2012b). Reference Memari et al. (2012b) is the only reference found that has attempted to derive kinematic equations for two-sided structural sealant glazing (2SSG) systems to predict the drift at which limit states are reached. There has been no such study for 4SSG systems. This paper represents a portion of a recent study presented in detail in Simmons (2011). The objective of the part of the study reported here was to develop two kinematic equations to predict the drifts at which limit states would occur. Sealant cohesive failure and glass cracking were identified as limit states, and corresponding drift levels were determined from full-scale tests. Such equations would also enable a designer to calculate the structural sealant effective shear strains for any given drift.

The kinematic equations were developed from the mockup geometry and the behavior of the glass relative to the frame as observed from video analysis and finite element modeling (FEM). The developed kinematic equations are linear and do not account for plastic deformation or cyclic loading. The kinematic equations were developed based only on the stick-built boundary condition.

## DISCUSSION OF PHYSICAL TESTING

The physical testing of the mockups was performed as part of a project of which this paper forms a portion of the analytical component. Memari and Kremer (2012c) provide details of the physical testing in a separate report. The following is a description of the constants, variables, observations, and conclusions from that report.

The dynamic racking test facility (Figure 1) used for the experiment consists of two horizontal-siding tubular steel beams, which represents spandrel beams on adjacent stories of a multi-story building. Each specimen was anchored to the sliding tubular beams at the mullions. A hydraulic ram (not shown in Figure 1) drove the bottom beam while the top beam was coupled to the bottom beam by means of a fulcrum and pivot arm assembly.

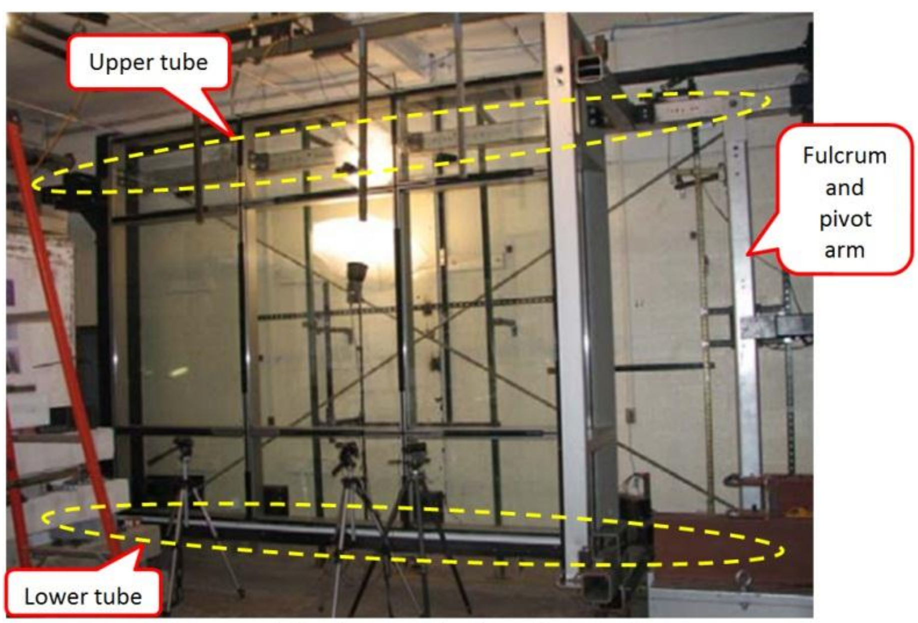


**Figure 1 – Typical Mockup Mounted on the Racking Test Facility**

The testing consisted of three identical mockups (Figure 1). The panels were glazed with Dow Corning 983 Structural Glazing Sealant in 2010. Test data in accordance with AC45 (ICBO 1991) from Dow Corning of the 983 Structural Glazing Sealant indicates an ultimate shear strain limit of approximately 190% to 200%. Mockup A is not reported in this paper. Mockup B was tested with a stick-built boundary condition and mockup C was tested with a stick-built-with-vertical-slip condition. As a result, the behavior of Mockup B was somewhat pure-racking whereas Mockup C allowed for the panels to slip vertically past each other. The basic dimensions of the mockup are shown in Figures 2 and 3.

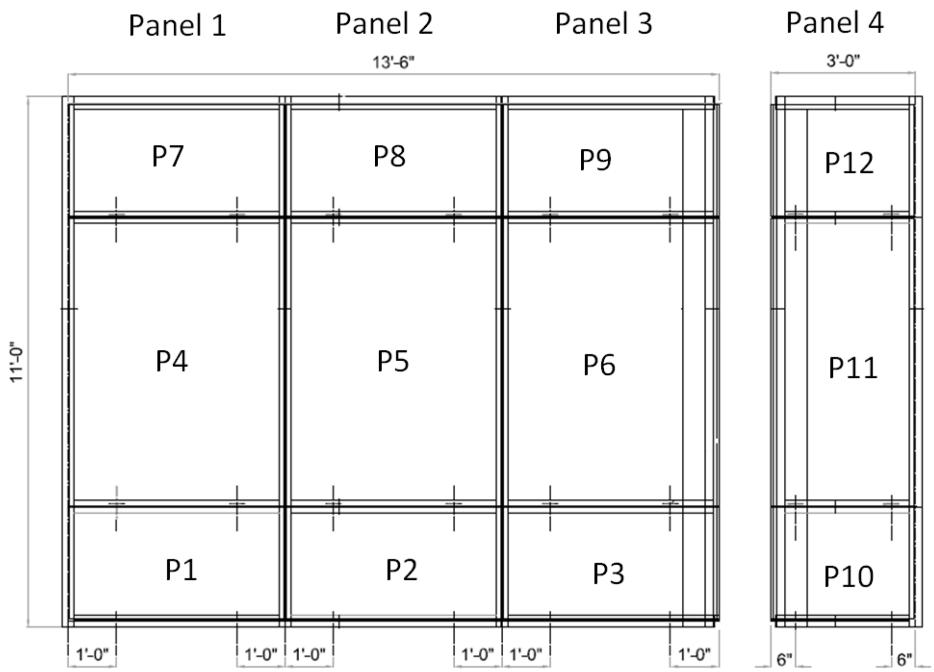


**Figure 2 – Elevation view of three panels and a perpendicular panel of a 4SSG curtain wall system (recreated from drawing provided by Bagatelos Architectural Glass Systems Inc.)**

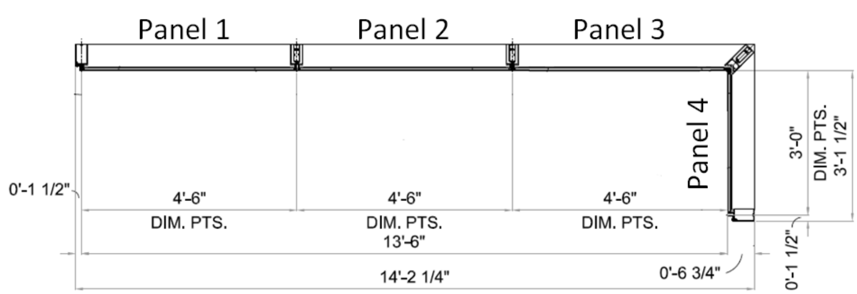


**Figure 3 – Plan view of three panels and a perpendicular panel of a 4SSG curtain wall system (recreated from drawing provided by Bagatelos Architectural Glass Systems Inc.)**

The failure modes of the mockup are defined are similar to those in Memari et al. (2006, 2011 and 2012b). Serviceability failure includes glass cracking or air leakage due to weather-seal and/or structural-seal failure. An ultimate failure is when a piece of glass, at least 1 $in^2$ in size, falls out from the mockup. The racking tests followed the procedure outlined in AAMA 501.6 (2009), according to which the racking drift vs. time, is induced in ¼" drift amplitude steps. In this research study, the racking was stopped after each ¼" step for inspection of any structural sealant damage. Figure 4 depicts this drift vs. time for Step 12 (maximum nominal amplitude of 3") and highlights the positive and negative amplitudes during the sixth cycle, labeled as C6.25 and C6.75. These are the targeted instants during the test for the video analysis.

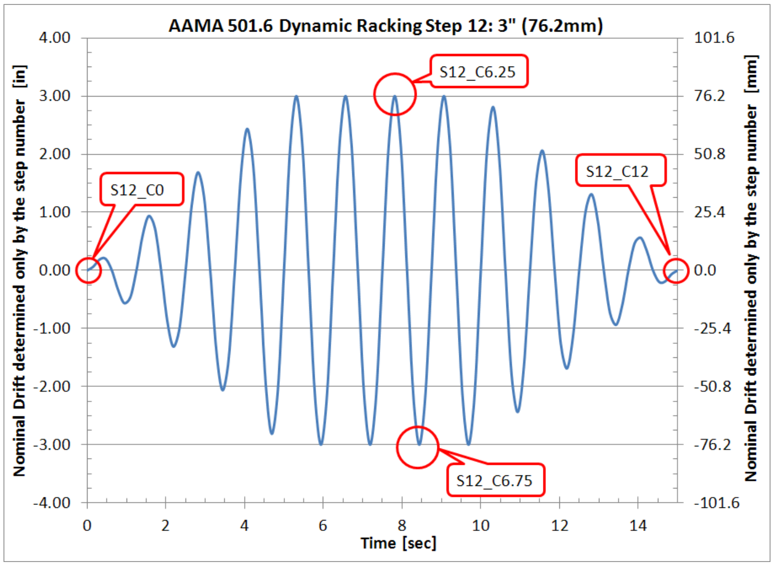


**Figure 4 – Drift vs. Time for Dynamic Racking Step 12 (Modeled after AAMA 501.6 2009)**

## FORMULATION OF KINEMATIC EQUATIONS

Two limit states were considered for development of the equations. The first condition was based on the limit at which the structural sealant (SS) fails. The second condition was based on the limit at which a glass pane corner makes contact with the side of an adjacent glass pane. Therefore, two different equations were developed to predict possible failure conditions. Each derivation assumes that the other condition has not occurred.

### Nomenclature and assumptions

The re-entrant corner of the mockup was ignored in the kinematic equation derivation to simplify the geometry as shown in Figure 5. Video analysis and FEM showed that each of the glass panes had distinct translations and rotations with respect to the aluminum frame. For simplicity of the derivation, each row of glass panes (Row 1 is P1, P2, P3; Row 2 is P4, P5, P6; and Row 3 is P7, P8, P9) is assumed free to translate in the horizontal direction, free to translate in the vertical direction, and free to rotate the same amount. The rotation of each glass pane with respect to the initial condition is defined as $\alpha_n$, where n refers to the glass pane number. The rotation of the mullion is defined as $\beta_m$. The rotation and change in the slope of the transom is defined as $\beta_t$, which was observed to be relatively small, and therefore it was assumed zero for the stick-built condition. The inter-story drift ($\delta$) is over height of the mockup (H). The drift ($\delta_s$) applied to the mockup is over the height ($H_s$) between the upper and lower sliding tubes.

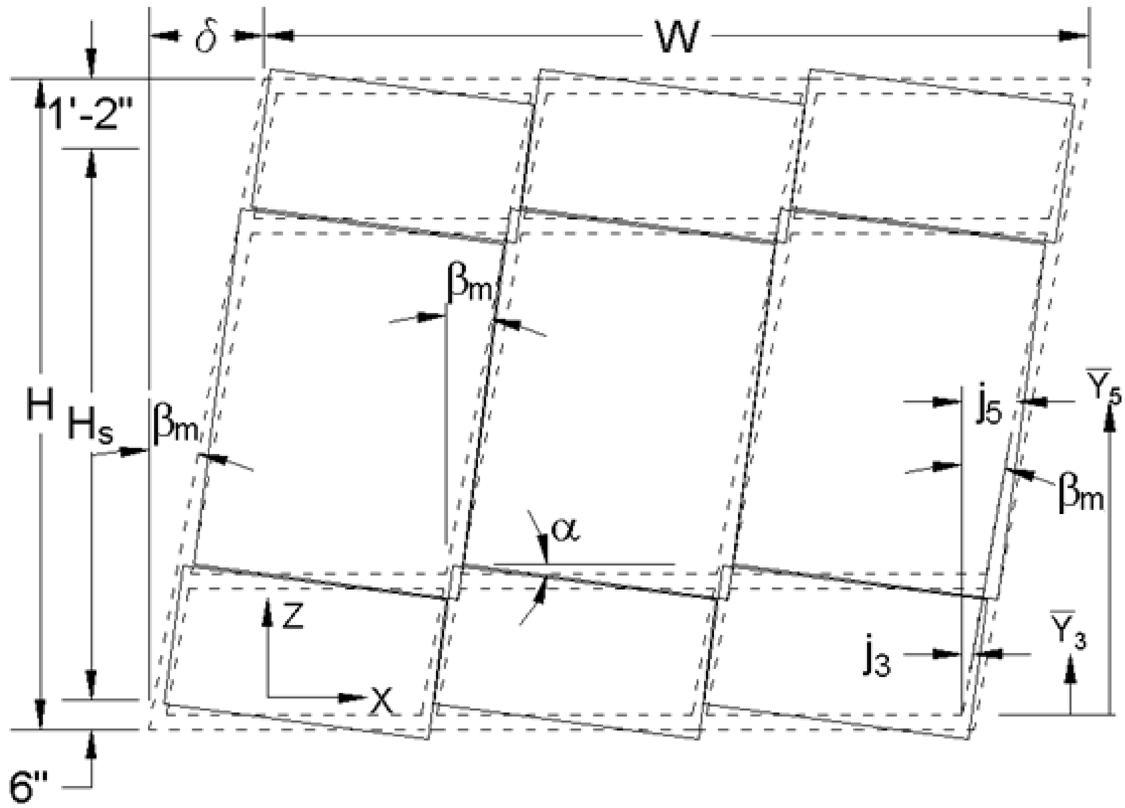


**Figure 5 – Exaggerated geometric rotation of the frame [dashed] and the glass panes [solid]**

The rotation values were determined from video analysis and FEM of the mockup when it had an applied inter-story drift of 1.99". These methods are discussed in detail in Simmons (2011), and the results are summarized in Table 1. The coefficient $c_{angle}$ is defined as the rotation of a glass pane divided by $\beta_m$, the theoretical value of the mullion rotations. From geometry, $\beta_m$ is the applied drift of the mockup ($\delta_s$ = -1.99") divided by the vertical distance between the boundary conditions of the test ($H_s$ = 109").

$$\beta_m = \frac{\delta_s}{H_s} = \frac{-1.99"}{109"} = -0.01826\, rad$$

**Table 1 – Measured rotations of the glass panes of stick-built mockup S12_C6.75 (Simmons 2011)**

| | Video Analysis (rad) | FEM (rad) | Average of Video Analysis and FEM, α [rad] | $c_{angle} = \frac{\alpha}{\beta_m}$ |
|---|---|---|---|---|
| Row 3 (P7, P8, P9) | -0.00179 | -0.00573 | -0.00376 | 0.206 |
| Row 2 (P4, P5, P6) | -0.00721 | -0.01241 | -0.00981 | 0.537 |
| Row 1 (P1, P2, P3) | -0.00432 | -0.00383 | -0.00407 | 0.223 |

The horizontal and vertical distances from the corner of the glass to the nearest interior corner of the mullion is respectively "r" and "s" as shown in Figure 6. This was used to form equations describing the movement of the glass corners relative to the mullions and transoms, which is the same as the deformation of the structural sealant. These equations represent the displacement of the nodes, which directly correlate to the longitudinal shear (Δr) and transverse shear (Δs) of the structural sealant. The Δr and Δs were assumed to be related to the effective shear (Δt) based on two methods. The first method is a linear relationship of longitudinal shear plus transverse shear. $\Delta t = |\Delta r| + |\Delta s|$. This is based on an equation from Shisler and Klosowski (1990). The second method is a quadratic relationship of the square root of the sum of longitudinal shear squared plus transverse shear squared. $\Delta t = \sqrt{\Delta r^2 + \Delta s^2}$. This is based on an equation from Sandberg and Ahlborn (1989). These two methods were also used to determine the effective shear from the video analysis and FEM of Simmons (2011).

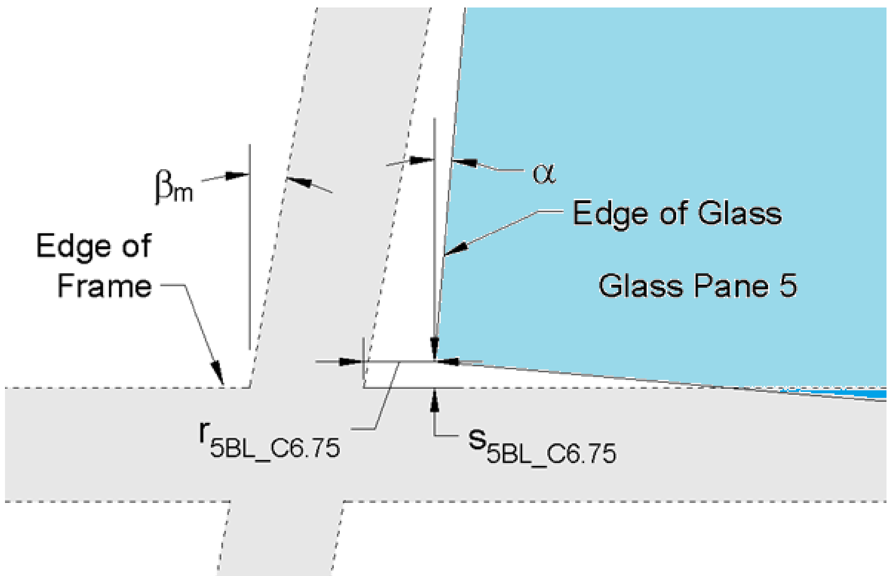


**Figure 6 – Exaggerated Geometric rotation of the frame [dashed] and the glass panes [solid]**

For this mockup, the thickness of the SS is 5/16" along the transom and 9/16" along the mullion. The shear failure of the SS is most likely to occur at the thinner SS first, and thus the thinner thickness will control the drift capacity of the mockup.

It can be assumed that kinematic equations for each limit state lead to smaller drift capacity predictions, which is more conservative. The reason is that the kinematic equations are based on the assumptions such as the glass acts as a rigid body, and the mullions rotate without deforming. However, the physical mockup is somewhat more flexible than the deformations assumed, thus yielding a larger drift capacity before SS failure.

**Shear strain limit of structural sealant prior to glass-to-glass corner contact**

The drift $\delta_{s,ss}$ represents the mockup drift at which failure of the SS occurs assuming that no glass pane corner has made contact with another glass pane. This is considered to be a serviceability limit rather than an ultimate limit state. When the SS first fails, there is not an immediate life-safety threat, but the repair costs to re-glaze the glass panes insitu can be significant. After this limit state is reached, a life-safety issue becomes significant as higher drifts are imposed and the SS failure propagates to the entire perimeter of the glass, which will lead to the entire glass pane to fall out.

The details of equation deviation in Simmons (2011) are not discussed here for brevity, only the final form of the derived equations is presented. Respectively, equations 1 and 2 determine the drift $\delta_{s,ss}$ from Method 1 (linear) and Method 2 (quadratic), where: X is the thickness of the structural sealant, $\gamma$ is the ultimate shear strain of the structural sealant, $h_n$ is the height of glass pane n, $w_n$ is the width of glass pane n, $H_s$ is the distance from upper and lower sliding tubes, and $c_{angle}$ is the rotation coefficient for the glass pane.

$$\delta_{s,ss\ 1st\ method} = 2 * \frac{X\gamma}{h_5+w_5} * \frac{H_s}{c_{angle}} \quad (1)$$

$$\delta_{s,ss\ 2nd\ method} = 2 * \frac{X\gamma}{\sqrt{h_5{}^2+w_5{}^2}} * \frac{H_s}{c_{angle}} \quad (2)$$

Substituting the properties of the SS, which are X=5/16", $\gamma$=2 (ultimate shear strain of 200%); and the dimensions of the mockup, which are $H_s$=9.33', $w_5$=4.5', and $h_5$=6', into Equations 1 and 2, it then yields:

$$\delta_{s,ss\ 1st\ method} = 2 * \frac{\frac{5}{16}in*2}{6ft+4.5ft} * \frac{9.33ft}{0.537} = 2.07in$$

$$\delta_{s,ss\ 2nd\ method} = 2 * \frac{\frac{5}{16}in*2}{\sqrt{(6ft)^2+(4.5ft)^2}} * \frac{9.33ft}{0.537} = 2.90in$$

The first noted SS failure for the physical mockup occurred at Step 16. The sum of the upper and lower tubes displacements ($\delta_s$) was 2.50" at C6.25 and 2.55" at C6.75 for Step 15 and was 2.67" at C6.25 and 2.73" at C6.75 for Step 16. So the failure most likely occurred when the sum of the upper and lower tubes displacement reached a drift between 2.55" and 2.73". The average of that range is 2.64", which is 28% more than the predicted value of 2.07" from Method 1 and 9% less than the predicted value of 2.90" from Method 2. It is possible that this failure could have occurred at a lower drift but was not detected by inspection until Step 16. A reason for the difference is that the sum of the upper and lower tubes displacement is slightly higher than the drift imposed on the mockup due to the flexibilities of the steel angles that connect the mockup to the sliding tubes. Neither Equation 1 nor 2 takes these two factors into account. Potential sources for a cause in an over-prediction of the drift could be imperfections of the SS bead or translations of the glass. An imperfection of the SS bead would lead to failure before the ultimate shear strain of 200% from the coupon testing is reached. The Equations 1 and 2 were developed based only on rotation and not translation. Any translation of the glass panes would cause additional shear strain on the SS, which would cause failure of the SS at an earlier drift limit. The calculated drift of 2.07" by Method 1 may be considered to be a conservative prediction of the SS failure. The calculated drift of 2.90" is then an over-prediction of the drift limit. The results from the example above using the kinematic equations support both Methods 1 and 2 as being reasonable.

**Drift ratio causing glass-to-glass corner contact prior to structural sealant failure**

The drift $\delta_{s,gap\_closed}$ represents the mockup drift at which glass panes make contact with other glass panes. This is considered to be a serviceability limit rather than an ultimate limit state. When a glass pane first makes contact with other glass panes, there is not an immediate life-safety threat, but this will lead to crushing of the corners and/or cracking of the glass pane. The repair costs to replace and re-glaze the glass panes insitu can be significant. After this limit state is reached, a life-safety issue becomes significant as higher drifts are imposed and the crushing of the glass pane corners or the cracking of the glass pane could lead to a piece of glass, size 1 $in^2$ or larger, to fallout from the mockup (ultimate limit state according to AAMA 501.6). The limit is also important to consider since the behavior of the mockup becomes more complicated. Non-linear behavior is expected after glass-to-glass-contact, SS failure, and/or plastic deformation of the frame. After this limit is reached, the FEM analysis and the kinematic equation for SS failure become less valid.

The details of equation deviation in Simmons (2011) are not discussed here for brevity, only the final form of the derived equations is presented. In order for glass-to-glass contact to occur, both the horizontal and vertical gaps between the glass panes must close. Equations 3 and 4 determine the drift, $\delta_{s,gap\_closed}$, at which the horizontal and vertical gaps close, respectively, where: $w_m$ is the width of the weather-seal along the mullion (horizontal gap between glass panes), $w_t$ is the width of the weather-seal along the transom (vertical gap between glass panes), $h_n$ is the height of glass pane n, $w_n$ is the width of glass pane n, $H_s$ is the inter-story height of the mockup (distance from upper and lower sliding tubes), and $c_{angle}$ is the rotation coefficient for the glass pane.

$$\delta_{s,horizontal\_gap\_closed} = \frac{2\mathrm{w_m}}{(h_3+h_5)(1-\mathrm{c_{angle}})} H_s \tag{3}$$

$$\delta_{s,vertical\_\mathrm{gap\_closed}} = \frac{\mathrm{w_t}}{(\mathrm{w_3}+\mathrm{w_5})*\mathrm{c_{angle}}} H_s \tag{4}$$

Substituting the dimensions of the mockup that are $H_s$=9.33’, $w_m$=¾”, $w_t$= ½”, $w_3$=4.5’, and $w_5$=4.5’, $h_3$=2.5’, and $h_5$=6’ into Equations 3 and 4, and using the assumed value of $c_{angle} = 0.537$, it then yields:

$$\delta_{s,\_horizontal\ \mathrm{gap\ closed}} = \frac{2*0.75\mathrm{in}}{(2.5\mathrm{ft}+6ft)(1-0.537)} 9.33ft = 3.56in$$

$$\delta_{s,\_vertical\ gap\ closed} = \frac{0.5in}{(4.5\mathrm{ft}+4.5ft)*0.573} 9.33\mathrm{ft} = 0.97\mathrm{in}$$

The drift at which contact occurs must be the larger of the two values predicted by Equations 3 and 4. The controlling value is 3.56” for the dimensions of the mockup being tested and assuming $c_{angle} = 0.573$. The sum of the upper and lower tubes displacements was 3.46” at C6.25 and 3.50” at C6.75 for step 20 and was 3.89” at C6.25 and 3.80” at C6.75 for step 21. So the predicted drift of 3.56” by Equation 3 suggests that glass contact will occur during Step 21. This was in fact the case as noted by the observations of the mockup at Step 21. This confirms the accuracy of Equations 3 and 4 to predict the drift at which glass-to-glass contact occurs, even though some SS failure did occur at Step 16 (approximately $\delta_s$ = 2.64”), and that there was major SS failure at Step 21 just before the glass contact occurred. However, it is possible that if the SS failure had not occurred before, a higher drift could have been reached before the glass contact occurred. If this was the case, then the predictions of Equations 3 and 4 would have been underestimated the drift capacity, which is more conservative.

## DISCUSSION AND CONCLUSIONS

Kinematic Equations were derived for the stick-built boundary condition for two limit states for 4SSG curtain wall systems. The first was the drift $\delta_{s,ss}$ at, which the SS fails due to the calculated effective shear strain reaching the ultimate shear strain (200%). The second limit was the drift $\delta_{s,gap\_closed}$ at, which one glass pane contacts another glass pane. Both derived equations made reasonable predictions. The equations predicted that structural sealant failure would have occurred at a drift $\delta_{s,ss}$ of 2.07” or 2.90” from Methods 1 and 2, when the actual observed drift was 2.64”. Furthermore, the kinematic equation predicted glass-to-glass contact at a drift $\delta_{s,gap\_closed}$ of 3.46” when the actual observed drift was between 3.50” and 3.89”.

Equations 1 and 2 may be used for any of the nine glass panes that are on Panels 1, 2, and 3. However, the glass panes in Row 2 (P4, P5, and P6) are considered to control over the glass panes in Rows 1 and 3, because Row 2 experienced the greatest amount of glass rotation and correspondingly had the highest assumed coefficient $c_{angle}$ of 0.537. Equations 3 and 4 were simplified by only using the coefficient $c_{angle}$ of 0.537. The accuracy of the equations would be improved by using the $c_{angle}$ coefficient from both the second row and either the first or third row (whichever controls).

The results of this study show that:

- Both methods of calculating the effective shear strain are supported by the kinematic equations applied to the stick-built 4SSG mockup at Step 16 when SS failure was first noted. The kinematic equation predicted that SS failure would have occurred at a smaller drift based on Method 1 and at a slightly larger drift based on Method 2.
- The kinematic equation predicted glass-to-glass contact for the stick-built mockup at Step 21, which did occur. However, the observations from the video analysis suggest that glass-to-glass contact would have occurred at a higher drift if SS failure had not occurred at Step 16.
- The movement of the glass panes relative to the frame becomes more complicated after either of the two limits defined in this chapter are reached. For any given mockup, either the glass-to-glass contact limit or SS failure limit will control, afterward the other equation becomes invalid.
- If the thickness of the SS differs between the mullion and the transom, then shear failure will occur at the thinner SS first, and thus the thinner thickness will control the drift capacity of the mockup.

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# A FRAMEWORK FOR CONSTRUCTION LABOR PRODUCTIVITY IMPROVEMENT IN EGYPT

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## ABSTRACT

Being the human input of the construction process, construction labors are the most dynamic elements of the construction industry. The cost of labor represents almost half of the overall construction cost. This paper proposes a framework to determine the significant factors impacting labor productivity, considering the Egyptian construction market as a case study. First, a craftsmen questionnaire is devised in light of a list of major factors affecting labor productivity that were specifically extracted from international studies on labor productivity. Second, a site-based survey is conducted with site operatives of different projects in Egypt through the craftsmen questionnaire to determine the particular factors affecting productivity in Egypt. Third, the factors that were commonly agreed upon by the surveyed sample of labors are evaluated and ranked by industry experts through a subsequent importance factor survey. Fourth, the most important factors are plotted in a factors' matrix, which enable the quantification of their relative influences on labor productivity and their interrelated influence through a third survey. Fifth, the output of the factors' matrix is planned to model labor productivity using system dynamics. This technique permits the identification of areas where effort should be exerted to achieve maximum labor productivity by testing the different management strategies that would improve the influencing productivity factors. Validating the model's findings is proposed through a work sampling study on a real-life construction project in Egypt to measure the productivity improvement before and after applying the recommendations extracted from the model. The analogy of this research is not to assign a specific focus on a particular trade; however, the surveys are intended to depict the major factors influencing labor productivity within an entire work site. Upon applying the model findings, the work sampling study is to be repeated to measure the improvement of manpower productive time, which improves the overall site productivity. In the interim, the main outcome of this paper is the identification of the factors with the most influence on labor productivity in Egypt, those were: availability of material, respect for craft workers and foremen, availability of health and safety training, availability of power tools, availability of drawings, absenteeism, jobsite orientation program,

coordination between the trades, and waiting for people and/or equipment to move material. As a future plan currently under implementation, the nine factors are to be incorporated in the factor matrix survey and in modeling productivity via system dynamics approach. The findings of the system dynamics model is expected to enable researchers and members of the construction industry to pinpoint the areas requiring more focus on improving labor productivity.

## KEYWORDS

Construction Management, Labor, Productivity, Craftsman Questionnaire, System Dynamics.

## INTRODUCTION

The construction industry in Egypt is suffering from severe market shrinkage. After the Egyptian revolution and its consequential political instability conditions, Egypt witnessed stringent funding issues. Both the public and private sectors have equally suffered from these circumstances. The government, as the major bid-letting entity for infrastructure, services, and industrial projects, currently lacks the power to issue new bids during the transition period; post revolution government officials are afraid from corruption allegations. On the other hand, the private sector has sustained heavy losses under the strain of revealed cases of corruption. This situation has reflected negatively on major construction projects, leading to a fierce competition between contracting companies to win new projects regardless of their size to survive this harsh period. The competition between construction companies forced them to minimize their costs.

Since the construction labors are the most dynamic element in the construction industry and their cost represents almost half of the overall construction cost (Rivas et al. 2011; Harmon and Cole 2006; and Hanna 2001), improving labor efficiency has become a target for construction companies in Egypt. One of the most efficient ways to increase labor efficiency is that of improving their productivity. Hence, by increasing labor productivity, less number of workers can achieve the same production rate, which leads to lower cost and enhances the company's chance to win new contracts.

## LITERATURE REVIEW

Labor productivity is an important topic that always gains researchers’ interest. Because of its importance as a key factor in the construction process, several studies of the factors affecting labor productivity have been carried out over the last three decades. Arditi (1986) conducted a survey among the top 400 contracting companies in the U.S. and found that further research in marketing practices, planning and scheduling, labor management relations, site supervision, industrialized building systems, equipment policy, and engineering design should be conducted in order to improve productivity.

Thomas and Raynar (1997) studied the effect of scheduled overtime over labor productivity, and concluded that scheduled overtime is a source of disturbance, as it may cause loss of labor productivity because of the shortage in providing the required materials and tools. This conclusion was supported by Hanna et al. (2005) who developed a model to predict the productivity loss due to extended overtime according to actual working hours and average working hours per week.

Thomas et al. (1999) studied the factors affecting labor productivity in erecting steel structures. He found that the material delivery method has influenced productivity; it is better to prefabricate the steel elements before site delivery and to directly erect the steel section from the truck. Hanna and Gondoz (2004) studied the effect of change orders on labor productivity; they developed a model that can predict the productivity loss due to change orders. Moselhi et al. (2006) investigated the impact of change orders on construction productivity using a neural network model to quantify this impact. Ibbs (2005) studied the impact of change timing on labor productivity. Data from 162 construction projects were statistically analyzed and a series of three curves representing the impact that change has on the labor productivity for early, normal, and late timing situations were developed. Hanna et al. (2005) studied the reason for absenteeism and quantified the impact of frequent absenteeism on labor productivity. Dai et al. (2009) studied the factors that affect labor productivity from labors' point of view. The study was initiated with 19 focus groups from different crafts to generate a list of factors that affect productivity; the effect of these factors on productivity was quantified by 1996 craftsmen in various working trades. Rivas et al. (2011) utilized craftsmen questionnaire to study the factor affecting labor productivity in mining project in Chile. The research identified the major productivity factors with higher effect on labor productivity to be materials, tools, equipment, trucks, and rework.

Other approaches, such as benchmarking and trend analysis have become a major area of productivity research. Arditi and Mochtar (2000) studied productivity trends in the U.S. construction industry. Park et al. (2005) developed a construction productivity data collection tool that has a standard metric definition for construction productivity. Lee et al. (2005) presented the development of CII Benchmarking and Metrics program which is an online data-base that provides participants in the US construction industry with sufficient data available.

## RESEARCH OBJECTIVE

The main purpose of this research is to develop a framework to identify the means for improving labor productivity, with a focus on the Egyptian case. This paper determines the major factors impacting labor productivity in Egypt through a set of surveys that have been conducted with both craftsmen and supervising teams of Egyptian construction projects to rank the factors impacting productivity. The weight of each factor is then intended to be quantified and the major factors are to be modeled using system dynamics to simulate the real life project. The future contribution of this research shall provide project managers with a crucial decision-making tool that will grant them the ability to effectively tackle such factors and subsequently maximize labor productivity. The scope of this research considers the Egyptian construction market as a case study, yet its outcomes could be generalized by following the proposed framework.

# RESEARCH METHODOLOGY

## Data collection

As shown in Figure 1, the first step of the framework to improve labor productivity is to identify major influencing factors. In order to achieve this objective, a craftsmen questionnaire is proposed to gather site-based operatives' opinions. Site operatives are the key players in executing construction activities; they are in the ideal position to express the factors that most affect their performance. The craftsmen questionnaire is devised in light of a list of major factors influencing labor productivity (Table 1) that were specifically extracted from previous studies on labor productivity. The craftsmen were asked to choose only the factors that affect their work from their view point. After collecting data from a sample population of 50 craftsmen, the number of times each productivity factor was selected by the craftsmen was counted. Then, the arithmetic mean of the total counts was calculated to eliminate the factors below the average (Table 2). Currently, more craftsmen are being called to participate in this survey, as the plan is to gather more than 500 responses from different craftsmen. The output of this process is a comprehensive list of factors which have the major influence on labor productivity in the Egyptian construction industry (Table 2).

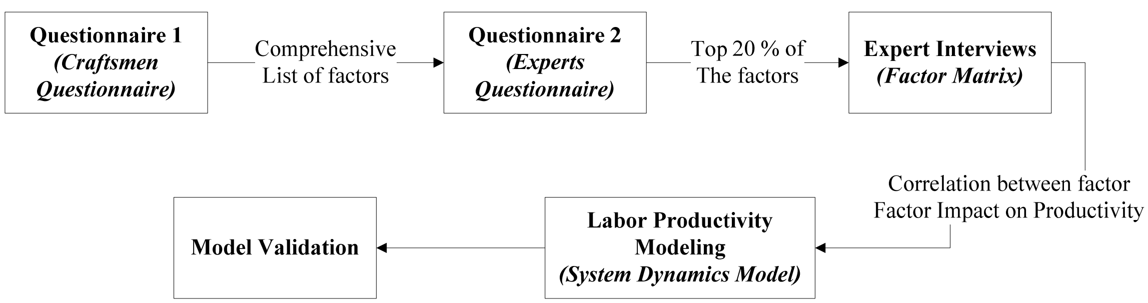


**Figure 1 - Methodology block diagram**

Second, industry experts were requested to rank the factors according to their relative impact on labor productivity. The target experts of this pilot survey were site-based senior employees who directly managed the workforce, including general foremen, site engineers, construction managers, trade superintendents, and project managers in Egypt. The first section of the questionnaire that was used to conduct this survey covered the demographic data of experts (Figure 2), while the second section enquired about the impact of each factor on labor productivity, using a 5 point Likert scale. Based on the responses of ten experts, the Relative Impact Index (RII) was calculated for each factor (Table 3) so that the top ranked factors were determined for conducting further studies. In order to ensure the quality of data, the questionnaires targeted the workforce, operatives, and supervisors working in the first category of the Egyptian contracting companies, only those who participated in Egyptian construction projects of a price not less than 30 million EGP (approx. 5M USD).

**Table 1 – Preliminary list of factors affecting labor productivity (Dai et al., 2009)**

| SN | Factor | SN | Factor |
|---|---|---|---|
| 1 | Inadequate instruction provided | 26 | Receiving compliments for doing a good job |
| 2 | Not receiving directions due to size of the project | 27 | Being notified of mistakes when they occur |
| 3 | Different languages spoken on a project | 28 | Foremen allowing crafts to work autonomously |
| 4 | Shortage of personal protective equipment | 29 | Lack of construction knowledge on behalf of foremen |
| 5 | Availability of consumables | 30 | Lack of proper resource allocation |
| 6 | Restrictive project policy on consumables | 31 | Proper managerial and administrative support |
| 7 | Availability of hand tools | 32 | Disregard of crafts' productivity improvement suggestion |
| 8 | Availability of power tools | 33 | Lack of communication among site management |
| 9 | Lack of power source for tools | 34 | Superintendent's people skill |
| 10 | Lack of extension cords | 35 | Incentive for good performance |
| 11 | Slow response to questions with drawings | 36 | Material storage area too far from workface |
| 12 | Misplaced tools | 37 | Coordination between the trades |
| 13 | Poor quality power tools | 38 | Slow decisions |
| 14 | Availability of material | 39 | Correct crew size |
| 15 | Poor material quality | 40 | Availability of skill training |
| 16 | Availability of bulk commodities | 41 | Jobsite orientation program |
| 17 | Errors in prefabricated material | 42 | Availability of health and safety training |
| 18 | Availability of drawings | 43 | Respect for craft workers |
| 19 | Inexperienced tool room attendants | 44 | Weather protection |
| 20 | Availability of crane or forklift | 45 | Craft workers' trust in supervisors |
| 21 | Availability of manlift | 46 | Maintenance of power tools |
| 22 | Waiting for people and/or equipment to move material | 47 | Pulling people off a task before it is done |
| 23 | Delay in work permits | 48 | Jobsite congestion |
| 24 | Out of sequence work assignments | 49 | Different pay scales for the same job on a project |
| 25 | Absenteeism | 50 | Respect for craft workers and foremen |

**Table 2 – First questionnaire results, The Top 30 factors**

| SN | Factor | Score | Rank | SN | Factor | Score | Rank |
|---|---|---|---|---|---|---|---|
| 27 | Being notified of mistakes when they occur | 33 | 1 | 31 | Proper managerial and administrative support | 29 | 16 |
| 42 | Availability of health and safety training | 33 | 2 | 37 | Coordination between the trades | 29 | 17 |
| 4 | Shortage of personal protective equipment | 32 | 3 | 46 | Maintenance of power tools | 29 | 18 |
| 39 | Correct crew size | 31 | 4 | 11 | Inexperienced tool room attendants | 28 | 19 |
| 50 | Respect for craft workers and foremen | 31 | 5 | 13 | Poor quality power tools | 28 | 20 |
| 2 | Not receiving directions due to size of the project | 30 | 6 | 14 | Availability of material | 28 | 21 |
| 3 | Different languages spoken on a project | 30 | 7 | 35 | Incentive for good performance | 28 | 22 |
| 6 | Restrictive project policy on consumables | 30 | 8 | 9 | Lack of power source for tools | 27 | 23 |
| 7 | Availability of hand tools | 30 | 9 | 16 | Availability of bulk commodities | 27 | 24 |
| 8 | Availability of power tools | 30 | 10 | 18 | Availability of drawings | 27 | 25 |
| 22 | Waiting for people and/or equipment to move material | 30 | 11 | 26 | Receiving compliments for doing a good job | 27 | 26 |
| 43 | Respect for craft workers | 30 | 12 | 32 | Disregard of crafts' productivity improvement suggestion | 27 | 27 |
| 10 | Lack of extension cords | 29 | 13 | 40 | Availability of skill training | 27 | 28 |
| 21 | Availability of manlift | 29 | 14 | 41 | Jobsite orientation program | 27 | 29 |
| 25 | Absenteeism | 29 | 15 | 45 | Craft workers' trust in supervisors | 27 | 30 |

**Academic Qualification:**

| | |
|---|---|
| Masters Degree | 3 |
| Bachelor Degree | 7 |

**Years of Experience:**

| | |
|---|---|
| 5-10 years | 6 |
| 10-15 years | 4 |

**Position in the Organization:**

| | |
|---|---|
| Quality Engineer | 2 |
| Site Engineer | 7 |
| HSE officer | 1 |

**Figure 2 – The demographic data for the participants in the pilot survey**

Based on the output of the second questionnaire (Table 3), the relative impact of each factor on labor productivity was determined. It can be concluded from Table 3 that the factor "availability of material" received the highest score in Relative Impact Index RII with a value of 6.48, and "inexperienced tool room attendants" got the lowest score of 2.2. Based on the Pareto principle, only the top 20% of the factors are proposed to be listed in a matrix called the "Factor Matrix" (Figure 3), which aims at quantifying the negative or positive impact of each factor on productivity. Besides, productivity factors have significant influence on each other, thus the Factor Matrix will be used for determining and quantifying the interrelationship between factors. This will provide the necessary numerical information for modeling labor productivity using systems dynamics. The purpose of limiting the factor matrix to the top 20 % of the factors was to allow the surveyed sample a reasonable time and minimize the effort for filling the factor matrix. By applying the Pareto principle, the top 20% of the factors were: availability of material, respect for craft workers and foremen, availability of health and safety training, availability of power tools, availability of drawings and absenteeism. It can be noticed that the following three factors have a RII equal to 5.12 which is almost the same RII for absenteeism, the 6$^{th}$ factor; therefore, it was decided to add them to the top ranked list and to be used in further analysis. These factors were jobsite orientation program coordination between the trades, and waiting for people and/or equipment to move material.

**Table 3 – Relative impact questionnaire results**

| Rank | Factor | RII | Rank | Factor | RII |
|---|---|---|---|---|---|
| 1 | Availability of material | 6.48 | 16 | Craft workers' trust in supervisors | 4.4 |
| 2 | Respect for craft workers and foremen | 5.64 | 17 | Receiving compliments for doing a good job | 4.28 |
| 3 | Availability of health and safety training | 5.44 | 18 | Lack of extension cords | 4.24 |
| 4 | Availability of power tools | 5.4 | 19 | Disregard of crafts' productivity improvement suggestion | 4.24 |
| 5 | Availability of drawings | 5.24 | 20 | Poor quality power tools | 4.24 |
| 6 | Absenteeism | 5.16 | 21 | Availability of manlift | 3.96 |
| 7 | Jobsite orientation program | 5.12 | 22 | Maintenance of power tools | 3.48 |
| 8 | Coordination between the trades | 5.12 | 23 | Shortage of personal protective equipment | 3.48 |
| 9 | Waiting for people and/or equipment to move material | 5.12 | 24 | Availability of bulk commodities | 3.36 |
| 10 | Different languages spoken on a project | 4.84 | 25 | Restrictive project policy on consumables | 3.28 |
| 11 | Being notified of mistakes when they occur | 4.72 | 26 | Proper managerial and administrative support | 3.28 |
| 12 | Correct crew size | 4.68 | 27 | Not receiving directions due to size of the project | 3.08 |
| 13 | Availability of hand tools | 4.52 | 28 | Availability of skill training | 2.76 |
| 14 | Lack of power source for tools | 4.48 | 29 | Incentive for good performance | 2.68 |
| 15 | Respect for craft workers | 4.48 | 30 | Inexperienced tool room attendants | 2.2 |

| | Availability of material | Respect for craft workers and foremen | Availability of health and safety training | Availability of power tools | Availability of drawings | Absenteeism | Jobsite orientation program | Coordination between the trades | Waiting for people and/or equipment to move material | Impact on Productivity | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | 5 | 4 | 3 | 2 | 1 | -1 | -2 | -3 | -4 | -5 |
| Availability of material | | | | | | | | | | | | | | | | | | | |
| Respect for craft workers and foremen | | | | | | | | | | | | | | | | | | | |
| Availability of health and safety training | | | | | | | | | | | | | | | | | | | |
| Availability of power tools | | | | | | | | | | | | | | | | | | | |
| Availability of drawings | | | | | | | | | | | | | | | | | | | |
| Absenteeism | | | | | | | | | | | | | | | | | | | |
| Jobsite orientation program | | | | | | | | | | | | | | | | | | | |
| Coordination between the trades | | | | | | | | | | | | | | | | | | | |
| Waiting for people and/or equipment to move material | | | | | | | | | | | | | | | | | | | |

**Figure 3 – The Factor Matrix**

## Modeling labor productivity

Labor productivity is proposed to be modeled by virtue of system dynamics. System dynamics is an approach to model complex problems. It was created in 1960s by Jay Forrester. It is a useful tool for modeling variables that change over time. System dynamic technique has gained recognition in the field of project management since its creation that can be used for supporting managerial decision regarding staff productivity, introducing new technologies and effort on rework discovery among many other applications (Rodrigues and Bowers, 1996). Tung and Ogunlana (2003) used system dynamics to model the dynamic performance of a construction organization. Mawdesley and Al-Jibouri (2009) utilized system dynamic to model project productivity; they concluded that planning, control, safety, motivation and disruptions are the major factors that affect productivity, and according to their model, further investment in planning would increase labor productivity.

The proposed model in this paper calculates a productivity index (PI) which is a function of the +ve or –ve impact of each factor on productivity multiplied by the value of each factor at a certain time. The value of each factor at a certain time is a function of the value of this factor at the pervious time and the interrelationship between the factor and other factors. This can be translated to an equation form as shown in Equations 1 and 2.

$$\text{Productivity}(t) = P_1 \times \text{factor } 1(t) + P_2 \times \text{factor } 2(t) + \ldots\ldots\ldots\ldots P_n \times \text{factor}_n(t) \qquad (1)$$

*where $P_1$, $P_2$…. $P_n$: are coefficients which represent the +ve or –ve impact of each factor on productivity from the Factor Matrix.*

$$\text{Factor } 1(t) = a_{12} \times \text{factor } 2(t-1) + a_{13} \times \text{factor } 3(t-i) \ldots\ldots + a_{1n} \times \text{factor } n(t-1) \qquad (2)$$

*Where: $a_{12}$, $a_{13}$, $a_{1n}$ are the coefficient of the interrelationship between factor 1 and each other factor from the Factor Matrix, and factor 2 (t-1) is the value of this factor in the previous period.*

The output of the Factor Matrix will be used in labor productivity modeling. As mentioned earlier, the Factor Matrix aims at quantifying the impact of each factor on productivity either negatively or positively. These values will be the coefficient ($P_n$). Besides, the significant influence of a factor on other factor, which was determined via the Factor Matrix, will constitute the ($a$) coefficients in the aforementioned equations. The model, currently under preparation, is proposed to simulate the labor productivity. If used efficiently, it can be used to evaluate the best case scenario to improve labor productivity among selected several strategies and test their effect on productivity. Some preliminary experiments were performed though to determine if it was possible to provide general advice to managers as to where to concentrate expenditure and efforts, based on the result of a sample system dynamics model. The sample model discussed the effect of adding the same attention to all factors, so the values {$F_1$, $F_2$, $F_3$….$F_n$ at time ($t_o$)} would be the same. After one time interval, the PI values have changed because the relative impact of the factors on each other modified the values of {$F_1$, $F_2$, $F_3$….$F_n$ at time ($t_1$)} and so on. For 5 time intervals the PI value showed the pattern illustrated in Figure 4.

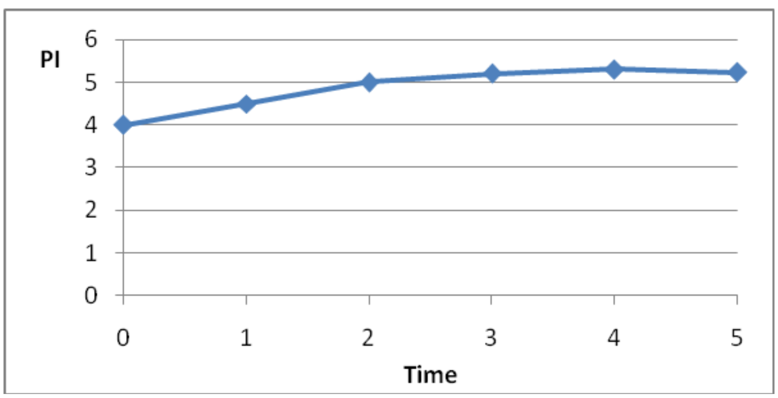


**Figure 4 – Illustration of the model behavior**

## VALIDATION

The validation step is proposed using work sampling method for measuring overall process productivity; work sampling aims at determining the proportion of productive time to nonproductive time in addition to determining the distribution of workers' time during the working day (Gouett et al., 2011). The notion behind work sampling is reducing the non-productive time, which provides the project with more productivity. Liou and Borcherding stated that *"In order to improve productivity,… one has to measure labor performance against some sort of standard before and after improvement measures have been introduced to reveal the usefulness of the corrective action"* (Liou and Borcherding 1986).

The proposed validation method for improvement is to conduct a work sampling study for three running construction projects. First, the work sampling study will be conducted in these three projects before applying the model findings to draw the line for the existing productivity index. Subsequently, the project managers for those projects will be advised with the areas that they can increase their efforts in order to achieve a tangible improvement in labor productivity. A three-month period will be given to the project manager to allow the application of the manager's course of actions for improving productivity. After the three-month a work sampling study will be conducted again to re-measure the proportion of productive time to nonproductive time. This will show whether these projects have gained an increase in the productivity or not.

## CONCLUSION

Construction productivity is an important field of research. Labors, as the human input in the construction industry and the dynamic resource in any construction process, gain more interest to study their productivity. This research aims to create a useful tool to be used by project managers to improve labor productivity. In order to achieve that, the main factors that affect labor productivity were determined via a craftsmen questionnaire, and then they were evaluated and ranked by industry experts. The findings of this stage are the main influencing factors which are availability of material, respect for craft workers and foremen, availability of health and safety training, availability of power tools, availability of drawings and absenteeism, jobsite orientation program coordination between the trades, and waiting for people and/or equipment to move material. As a future work, the nine factors are to be incorporated in a Factor Matrix survey whose outputs will be applied in modeling productivity via System Dynamics approach. Following this framework will enable researchers and members of the construction industry to pinpoint the areas requiring more focus on improving labor productivity.

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# DESIGN PHILOSOPHY OF THE TRADITIONAL KUWAITI HOUSE

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Architecture represents the art of planning, designing, building and decorating.Alsoit reflects the identity, culture and social realities of whole civilizations, captures and converses with the environment of its inception be it the natural climatic environment or the values, norms and belief systems. The study of a given architecture, therefore, implies extensive knowledge about the society, its system of reference and its climate to properly identify and interpret the manifestations of all these factors in the art of building.

The study of the traditional Kuwaiti architecture, whichis the focus of this paper, requires an understanding of both the natural and social environment of Kuwait. The traditional Kuwaiti house was conceived in a time when traditions and rules drawn from Islamic precepts had the upper hand. It was also built in a natural environment characterized by extreme temperatures, the people who built them were simple people, with very little wealth, but very resourceful.

All these factors produced a vernacular architecture that is highly compatible with various aspects of its environment. However, after the discovery of oil in the Gulf region in 1930, and the financial enrichment of the country, people started to opt for more modern styles of building for their houses. Such new houses proved very unbefitting to neither the Kuwaiti climatic environment nor the Islam-informed social climate.

This paper introduces the traditional Kuwaiti architecture and highlightsthe positive attributesit enjoys and which should be preserved and optimized rather than supplanted by the introduction of new 21$^{st}$ Century architectural designs, thus contributing to the preservation of the ecology of the region and the world at large and accommodating the needs of Muslim desert dwellers such as the people of Kuwait in terms of comfortable and culturally aware habitat.

## Introduction

The symbols and suggestions enclosed in the art of the traditional Kuwaiti house were not a coincidence. Al-Wail (2003) affirms that the desert nature, its harsh life and human experience were the muses of the modest Kuwaiti craftsman whose memory was tattooed by the unforgiving nature of the desert, itscruel sun and ardent heat. He sought solace in the clement night sky with its stars and moon, and drew from them vivid symbols that he skillfully crafted through the medium of his hands and his unspoiled nature. The same impression is conveyed by the whole array of indigenous Kuwaiti art which, aided by its contact with surrounding cultures, managed to beautifully capture the feeling of the surrounding nature and environment and embody the people's way of life.

Thetraditional Kuwaitihouse is characterized by its simple design that fits perfectly into the local environment (Al-Wail 2003). The organisation and configuration of internal space was contingent on the economical and social status of the Kuwaiti family occupying it. Even though most houses had a rather austere nature manifested in their plain appearance from the outside. In the inside, the abstraction is manifest in the adoption of simple geometric forms, drawings of the local flora and some engravings with no representations of humans and living things as this is forbidden in Islam(Al-Wail 2003).

The traditional Kuwaiti house greatly respected local customs, traditions and norms drawn from old wisdom and from the teachings of Islam. One of its distinctive features is the protection and the sheltering it affords to the privacy of its occupants and its inner atmosphere,which is meant to be in clear contrast to the outer world. This is especially true for the Women of the house, as the common understanding of the Islamic teaching in the region is that women should keep as much as possible to the house and only leave it when there is no other alternative. Also, they should be sheltered from foreign male gaze, including visitors.

Hence, The focus of the house wason the interior. It sought balance between the strict need for privacy, especially females',and the Arab and Islamic obligation of hospitality (Wali 1990). This was achieved through the division of its courtyard into different spaces of varying capacities open from one or many sides onto various rooms, and providing open but separated spaces for both male and female occupants to both live and receive guests.

## The shape grammar of the traditional Kuwaiti house

Kuwaiti architectural shape grammar (ASG), which has existed for the past 200 years, was based on the 1400-year-old tradition of Islamic shape grammar. In order to understand the Kuwaiti ASG, we have to first learn about the Islamic ASG concepts and the rules that govern them(Kazerooni 2002).

The Islamic built laws are inspired by the Islamicphilosophy, ideology, law, and the requirements of socio-cultural forces in Muslimlife (Hakim 1986). The built laws or principles as mentioned in Islamic jurisprudencebooksillustrate the responsibilities of both individuals andauthority in Islamic law (Hammad 1997). They have come to constitute a consistent and systematic set of laws or what is termed “Fiqh”. Hakim (1986) defines Fiqh of building processes as: "the mechanism of interpreting and applying thevalue system of the shari'a (Islamic divine law) within the processesof building and urban development... its primary sources, the Qur'anand the Sunna (tradition and deeds of the Prophet of Islam) are crucial for thetransfer of the value system to design and urban form."

Islamic built laws were used to define the rights and responsibilities of people and gave guideline on how to satisfy one's preferences in terms of habitat without impinging on other people's rights and interests (Al-Ibrahim 2003). In this sense, Akbar (1988) points out that the Islamic principals have defined theuser’s rights in terms of how to build, alter or extend his/ her property. Some of the Islamic building principles have beencrystallizedthrough the solutions resulting from the conflicts thatsometimes occurred between individuals themselves or between the individuals and the governing authority (Hakim, 1991 and Ibn Al Rami1995). These principals provide a flexible framework to the propertyuser/owner that enables him/ her to change his property without harming his neighbours and violating their rights.

The major preoccupation of the Muslim Kuwaiti architect was therefore to build a house that will protect the occupants from the scorching heat and sun in the day and insulate them from the freezing temperatures of the desert at night through various building techniques, the wind scoop being one of them; there was also the need for lighting before the advent of electricity which was satisfying by ingenious skylighting designs. This is from a climatic point of view; from the social and cultural point of view, the house had to provide a safe haven for the women residing inside, protect them from the outside world and its curious gaze and even inside, provide them with private and isolated enough spaces to accommodate guests, mainly males, according to the stringent requirements of Arab hospitality while allowing women a measure of freedom to go about their daily occupations.

Therefore, the shape of the house, the organization of spaces, the shape of the house's components are designed according to theinteraction between the factors highlighted above.

In Islamic architectural shape grammar, the most comprehensive range of features does not make a coherent external architectural shape grammar. It was achieved by expressing each element of the building individually. There was no attempt to collect numerous spaces and volumes in one great envelope to describe as single mass. Each component stands identified in its own right. It is expressed externally as a part of a sequence of limited structures. The coordination, clear expression and articulation of individual components together supply the fundamental discipline. The emphasis was given to the function of each part in relation to another and how each part functions independently (Kazerooni 2002).

Secondly, Islamic ASG was not automatically revealed in its forms and the function it serves. The dome, Liwan (Loggia) and clusters may be emphasized or diminished as required within their regional variant, each containing elements that display the essential structural form.

Thirdly, the additions to the original plan are consequently never hampered by an inherent principle governing all parts in equal manner with an exception of four Liwan plans on the latter Islamic buildings. Traditionally, a Kuwaiti house is said to never be complete, with flexibility to enlarge a given structure in almost any direction by adding units, totally disregarding the form of the original structure (see Figure 1) (Kazerooni 2002).

Fourthly, enclosed space defined by walls, arcades and vaults is the most important element of Islamic architectural shape grammar. Hence, the basic courtyard design was the basis of Islamic design (see Figure 2) (Kazerooni 2002).

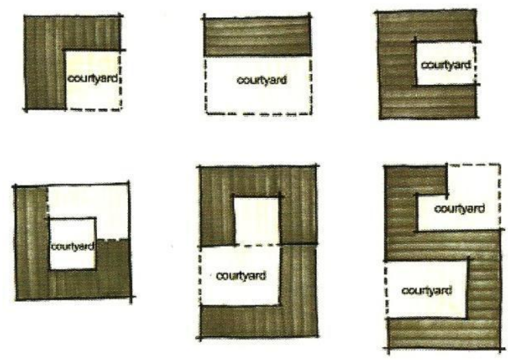



Figure 1: Islamic building-various types of courtyards and enclosures (Kazerooni 2002).

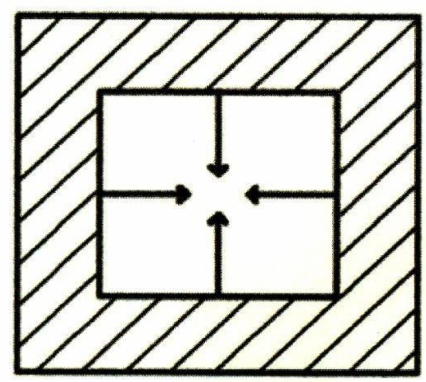


Figure 2: Islamic inward looking plan (Kazerooni 2002).

## Most important architectural elements in traditional Kuwaiti house

The architecture of a traditional Kuwaiti house was to a large extent improvised and spontaneous due to the lack of scientific expertise and the heavy reliance on instinct and local skills acquired through continuous practice. Low financial capacity and the limited materials available locally for construction had their say on the nature of this architecture. Notwithstanding, it was a successful example of a construction that fitted perfectly within the merciless desert climate and responded adequately to the basic need of its occupants (Abdullah 1986).

The literature informs us that the elements of the traditional Kuwaiti house are therefore the product of an interaction between the occupants, its natural environment and its social surroundings. The architectural details were all created as a result and in reaction to the unwelcoming natural environment. Rudofsky (1964) affirms that most traditional houses are the practical and theoretical response to human interaction with the environment, and that these traditional houses were build without architects in a modern sense, which means without the strict and precise modern architectural rules. The specificity of the traditional Kuwaiti house lies precisely in this spontaneous, unsophisticated and improvised mode of building, which manifested as follows:

## - Courtyard

An inner courtyard is a common architectural element found in most ancient civilizations such as ancient Egypt, Western Asia and Rome. The particularity of Islamic inner courtyards is the fact that they came as an architectural response and fulfillment of Islamic precepts that command modesty and introversion. Islamic buildings were to reflect this parameter and create as stark a contrast as possible with the outer conditions. This, environmental contrast, is one of the basic rules underlying Islamic architecture;It is where the concept of an inner courtyard originated from in the traditional Kuwaiti house (Dostal 1970).

It is commonly said that courtyard is the lung of the house. It is indeed the principal outlet for the people of the house, especially women who rarely set foot outside. It is an architectural principle that promotes the introversion upheld by Islam, and strives to achieve reconciliation between Arab hospitality and the need for privacy inside the house. Traditional Kuwaiti houses all had one or more open courtyards inside which were surrounded by walls to delimitate the boundaries of the house vis-à-vis the outside world and the neighbours' houses and send the message that inside those walls is a private space that is not to be violated (see Figure 3) (Dostal 1970).

The inner courtyard was surrounded by different rooms overlooking them exclusively with their doors and windows to stress the need for privacy and to facilitate the movement between different parts of the house (see Figure 4). The walls surrounding the courtyard were usually quite high so they somewhat protected the house from strong winds and dust which is another proof of the high compatibility of the traditional Kuwaiti house with its natural environment (Al-Azmy 2000).


Figure 3: Courtyard of one traditional Kuwaiti houses, Bayt Al-Bader(Researcher photo).

Figure 4: Courtyard surrounded by rooms, Bayt Al-Bader(Research photo).

## - Loggias (Liwan)

Loggias are very important architectural elements in the traditional Kuwaiti house that also came as a response to geographical and social conditions. The loggia consists of a space open onto some of the rooms from one side and onto the courtyard from the other side (see Figure 5, Bayt Al-Bader). Note that the direction of building was always toward the courtyard rather than the outside. Loggia took the form of a porch whose roof started at the side of the room where the door is situated, and end on a wooden bridge supported by stone or wood columns that were sometimes imported readymade from abroad (see Figure 6, Bayt Al-Bader) (Abdullah 1986).


Figure 5: (Researcher photo).

Figure 6: (Researcher photo).

This architectural element is widespread in traditional Kuwaiti houses as well as intraditional houses in the Gulf region. And loggias mostly existed in wide and level spaces where this structure fits best, since they require a continuation of space in front of them and serve as an interface between the inside and the courtyard of the house.

That is why such structures are not prevalent in mountainous countries like Lebanon since the open flat spaces needed for loggias to expand on are not available. It is usually used during the day to receive close relatives, to sit in the shade, and take the morning tea or as a place to mingle for the women of the family. Non-family guests are received in the guest room; the loggia was for family only and as a living room at times (Ragette 2003).

This architectural style was also common in some neighbouring countries such as Iran, northern Iraq and northern Syria where Loggias were built along the width of the rooms that opened on them and were usually facing north to make the most of the cool wind that blew from that direction and distribute it inside the different rooms (Abdullah 1986).

In addition, Ragette (2003) derived a link between the loggia structure with Bedouin tent, since they too are closed from three sides and only open from the forth for aeration, the higher part of tent is always their middle and the space in front of them is also considered an extension of them (see Figure 7).Ibrahim (1985) did not confirm the Ragette derivation of the loggia from the design tent, however, Ibrahim argued the loggia was developed during the pre-Islamic era by the people of the kingdom of *Hadr*which is one of the oldest Arab kingdoms (see Figure 8), then the style was taken up by various subsequent kingdoms until the first century after the advent of Islam when such structure were to be found in public buildings such as schools, hospitals, mosques and rulers' palaces and from then spread to private dwellings all over the Islamic world.

Figure 7: (Scarce 1985).

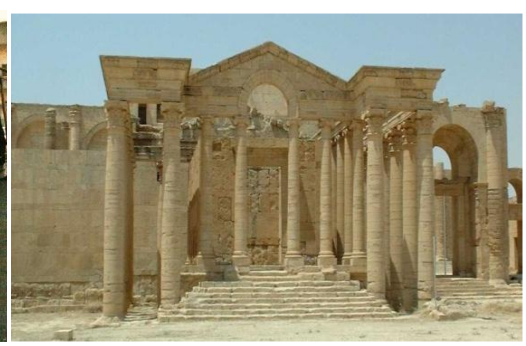
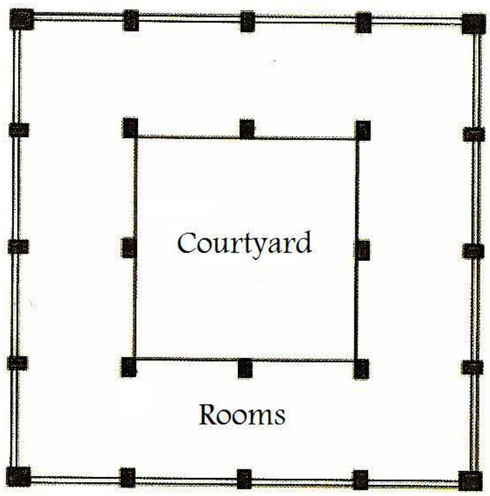


Figure 8:(http: //www.fnkazem.net).

Nevertheless, the literature's opinion on the loggia, is differ fromRagette and Ibrahim opinions, which is that the courtyard of the traditional Kuwait houses, were built with single row of rooms around the inner courtyard (see Figure 9). This single row of rooms provided the necessary privacy, even though it had a disadvantage. The inner wall was directly exposed to the sun, due to this, they were unable to keep the windows in the inner wall open in order to make the cross ventilation. Therefore, they innovated a new layout design, which provided an additional inner row of series columns to act as buffer zone between the courtyard and the rooms to keep this area shaded during daytime (see Figure 10) (Kazerooni 2002).



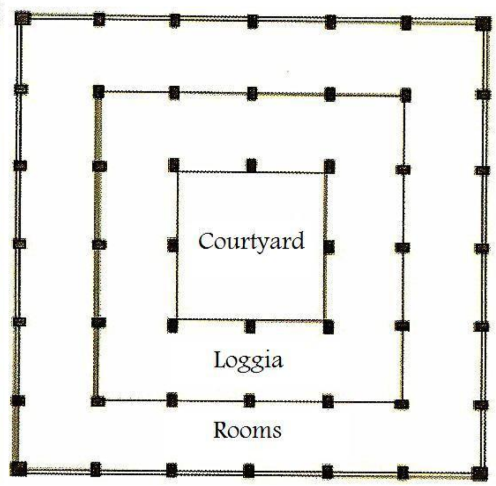




Figure 9: Single row (Kazerooni 2002). Figure 10: Double row (Kazerooni 2002).

## - Wind towers

It is impossible to talk about the traditional Kuwaiti house without reference to the very important constructional element that is the Wind tower (see Figure 11). Wind towers were crucial means of softening the impact of the desert's scorching heat. They were either very tall to moderately tall, either luxuriously built or displaying only the basic elements and finally they were either built of mud bricks or coral rocks but they all shared the faculty of being durable, stable, strong and regardless of any additional embellishment, they were all eye catching and beautiful.

Figure 11:(Avézard 2007).

Traditionally, wind tower were placed on the house roof and could reach as much as fifteen metres high, and each house used to have one or more towers depending on the requirement and financial capacity of the owner. Two kinds were common in the traditional Kuwait houses which are wind tower and wind scoop.

First, the wind tower is a cubic shape and entirely open from four directions and able to trap cool air in any direction (see Figure 12). The wind tower system involves wind coming from one direction and pushing the air inside the room by hidden duct inside the walls. And the hot air that was generated in the room and pocketed at top of the duct is released through the duct in opposite direction that of the inlet ducts like the flue of the chimney (see Figure 13). If the direction of the wind changes, the direction of wind entering in the duct and escaping in the opposite direction also changes. The pressure in the air which travelled inside the duct gained speed, and the air increased the speed of the cool air circulation entering and sending the hot air out forms a cooler current inside the room, and in this way the room is air conditioned. And when the air circulation is not needed then the shutter of the wind tower is closed (Wahbi 1987).

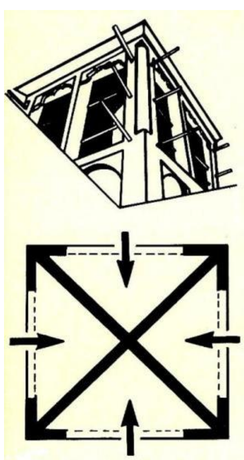


Figure 12: (Al-Hajji 2004).

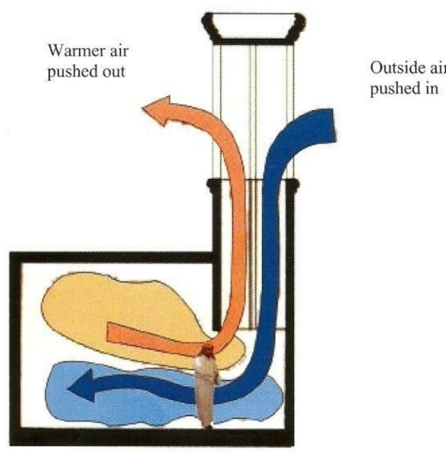
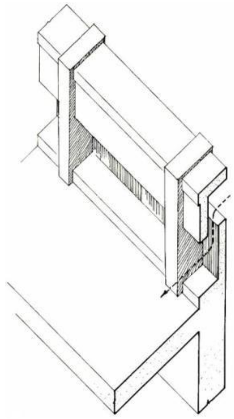
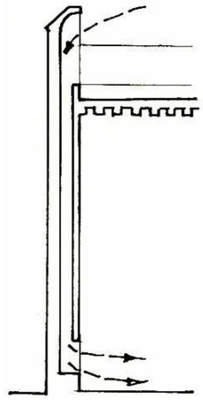



Figure 13: (Wahbi 1987).

Second, the wind scoop is a rectangle shape and open from one directional flow of air (see Figure 14). The wind scoop function was only to let in the air from outside and supply it to the rooms below though hidden duct inside the wall (see Figures 15 and 16). It is usually placed with its open interface facingnorth or northwest sides to catch directional airflow. The windows in the rooms have to be kept open so that the air pressure pushes out the hot air in the room through the door or windows, this is not necessary for the wind tower as the inflow of air is pushed out through the wind tower itself (Wahbi 1987).





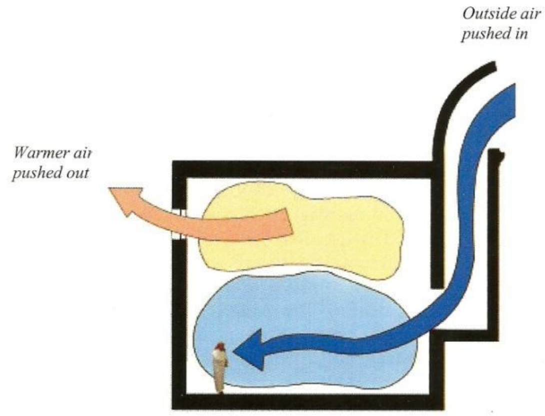



Figure 14: (Al-Hajji 2004).Figure 15:(Al-Hajji 2004). Figure 16: (Wahbi 1987).

Al-Wail (2003) sustains that the wind towers are not an original Kuwaiti architectural symbol. They were a Persian invention that found its way into Kuwait through the trade and economic relations that the two countries used to entertain with each other, and through the migration of some families that were living along the coast of Persia and chose to settle in Kuwait. With time, the wind towers became an integral element of Kuwaiti architecture. The very name given to these structures in Arabic: *Bagdeer*comes from Persian and means both wind tower and wind scoop.

The literature reveals that the wind towers go further back in history than even Persia. Traces of these structures were found that date back to the Assyrian time as this dynasty had spread its rule over the best part of the Middle East after the Sumerian civilization and the Babylonians under Hammurabi. This structure was also found in Persia in Arg-E-Bam near Yazd (see Figure 17). This early form was known as wind scoops. It was basically a tube that collected the air and made use of the outside pressure to push it along the device; the air then gained speed in the tube and travelled down to the rooms. These basic structures were later developed into sophisticated wind towers (Haider 1995).

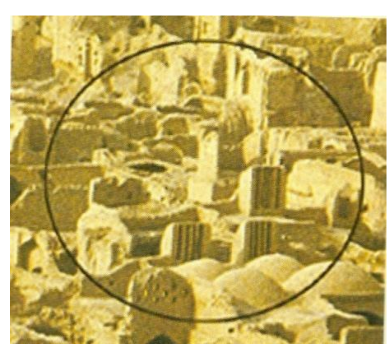


Figure 17: Arg-E-Bam – 2000 years old wind scoops (Haider 1995).

## Conclusion

Traditional Kuwaiti buildings speak volumes about the history of past civilizations that populated the region and left their print on each and every aspect of them. They also bear witness to the harsh climatic conditions the region is subject to and reflect the beliefs and social norms governing the society they originated in.

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