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eWork and eBusiness in Architecture, Engineering and Construction

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Preface

The first European Conference for Product and Process Modelling (ECPPM) was held in Dresden, Germany in 1994. One could ask, is the conference title still appropriate?

We, as conference organizers, argue it is since currently architects and engineers are challenged to develop intelligent solutions to substantially reduce the carbon footprint of buildings and other built artifacts. It is well known that the construction and operation of buildings contributes globally to approximately 40% of the CO_2-Emissions. This must be reduced as quickly as possible.

Consequently, the products of our sector have become totally different to what we saw back in 1994. High performance windows, additional layers of insulation, heat recovery systems, high performance lighting systems, energy micro-generators, advanced monitoring and control systems add new features to the products of the AEC-sector and allow us to reduce the carbon footprint of buildings. One could say that the role of buildings changes from an energy consumer to an energy provider. New infrastructure systems appear on the market, such as on-shore and off-shore wind farms, solar-thermal systems, or diverse types of micro-generators. They are the enablers for new technologies like electric vehicles or large scale energy storage systems. These new products also promote a restructure or modification of existing infrastructure systems, such as traffic networks, electricity distribution grids, etc.

However, the product life-cycle of built artifacts is extremely long compared to products of other industry sectors. Therefore, we must develop innovative business concepts and the underpinning process models which allow us to deliver both, (i) new products based on new design concepts and technologies and also (ii) new processes supporting the introduction of new business models and value added services.

The clients of the AEC-sector expect better "service delivery"–one-stop-shop solutions are preferred. Therefore, our sector must develop new collaboration models which enable the easy integration of specialists in the supply chain and simultaneously simplify the "interaction" between clients and service providers. Our sector needs process models that support Architects and Civil Engineers to maintain their leading role in delivering their products but also enabling them to integrate specialists from other disciplines, such as Electrical and Mechanical Engineers and IT-experts in the relevant design, manufacturing, and maintenance activities.

Consequently, innovative ICT-solutions are required to master the more complex design, construction, commissioning, and operation processes, to coordinate the growing number of stakeholders involved, and to better understand the overall performance of our products and the interaction of the subsystems and individual components.

The Peer-Reviewed Papers of the 8th ECPPM presented in this book address the aforementioned challenges.

These proceedings start with a chapter on 'Innovations'. We want to highlight the importance for high-quality achievements in our discipline and therefore present the contribution of the ECPPM-2008 Awardee as the first paper in this book, followed by two papers describing future visions for research in our discipline.

The sections about *Advanced Computing in Engineering* and *Simulation & Optimisation* focus on the development of innovative ICT solutions to support the Design Processes. They are complemented by two papers focusing on *Computer Aided Teaching and Learning* which illustrate the needs and potentials to embed IT-related subjects into all levels of curricula in the Architecture and Engineering domain.

The chapters on *Building Information Modelling* and *Collaboration and Process Modelling* address the 'core areas' of the ECPPM conference series.

The *European Group for Intelligent Computing in Engineering* (EG-ICE) is represented with six invited papers at our conference. The high-quality papers illustrate the broad spectrum of ICT-support for Engineers across the whole life-cycle of built artifacts.

We have decided to bundle papers in the thematic area of *IT for Energy Efficiency* to highlight the importance of this topic for our future work but also to illustrate how important the recent achievements in the area of Product and Process Modelling are for the success in this field.

The section entitled *Hardware-Software Platforms for Facilities and Energy Management* emphasizes on the integration of research achievements from multiple disciplines; Electrical and Microelectronic Engineering, Computer Science, and Civil Engineering. The precondition for the horizontal integration is the availability of BIM, delivering a consistent and consolidated framework for holistic building performance data management.

The section *Information Technology for Optimised Building Operation* presents three aspects of complex systems engineering; (1) ICT-support for information consolidation and aggregation, (2) ICT-support for Building Control using Artificial Intelligence, and (3) ICT-support for Diagnosis and Maintenance Management. The enabler for the life-cycle-oriented integration is the availability of holistic, consistent Process Modells and the capability for Semantic Data Modelling.

Finally, the section *ICT for Energy Efficiency in Buildings* bundles papers reporting about ongoing research in the Seventh Framework Programme of the European Union with an emphasis on Business Modelling and Simulation.

The success of each conference depends on the commitment and active participation of all people involved in it. We would like to thank everyone involved in the preparation of these proceedings for their time and effort invested to make this book and the conference a success.

Karsten Menzel & Raimar Scherer
Pieter de Wilde, Yaqub Rafiq
Cork, Dresden, Plymouth, July 2010

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Innovations

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Improving formalizing expert knowledge in construction: From ontology-based modelling to creating sustainable services

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ABSTRACT: This paper resumes a series of works on formalizing expert knowledge by its actionalizing and gives an overview of a conceptual approach for capitalizing such knowledge in the construction domain. Considering an ontology-based method we have developed to acquire and represent the expert knowledge involved in the conformity checking process, this research extends and improves it by putting together formal semantic models, service-oriented approaches, and formalized actionable knowledge. This is done by developing the information kernel, which capitalizes the knowledge indispensable for formalizing expert practices and is dynamically validated by usage. The information kernel is enabled by services that guarantee its functionality, semantic coherence and sustainability. We highlight the interdependence of developing the information kernel for formalizing expert knowledge and creating such services and we show that this approach leads to developing sustainable services. Practically, the proposed method can be implemented as a cross-pollination space for construction, the conceptual methodology of which we briefly discuss. The paper is concluded with the scope of research perspectives and priorities of our future work.

1 INTRODUCTION

This paper introduces an improved approach for formalizing expert knowledge by integrating sustainable services. This work is based on and extends our ontology-based method for knowledge capitalization in the context of the conformity checking model in construction.

The multidisciplinary nature of the construction domain, the large amount of expert, non formalized knowledge and the semantic inconsistency of information coming from different application contexts are among the main criteria which make the process of knowledge formalizing very complex and effort-consuming.

In our previous research on (semi)automating the process of checking the conformity of a construction project against a set of technical construction rules, we proposed a formal ontology-based approach allowing partial knowledge formalization, as well as identifying the scope of the challenges to be addressed. Among trans-disciplinary factors to be taken into account in improving knowledge formalization of expert knowledge, we particularly focus on the following ones.

Today, the *service sector* is believed to be one of the major sectors redefining the global economy as a services-oriented economy, in which services are present in the core of all economic processes. Furthermore, services are widely used in paradigms of conceptual modelling and technical implementation. In other words, with respect for *service orientation* at multiple levels of technology and business, we analyze the problem of knowledge capitalization from the service-oriented point of view for development and integration (Erl, 2008). We believe that such current services-oriented trends increase the effectiveness of modelling, as they allow the dissemination of interoperable scientific knowledge and practical intelligence throughout different domains.

While underlining the *necessity of rich understanding* of the environment to be modeled and the usage of ontology-based approaches to do so, it is also important to dynamically adapt domain ontologies to different contexts and usages. This is one of the main features of the *knowledge society* (Stehr, 1994), (David & Foray, 2002) and many of the *idea creation processes*, *experience actionalizing* and *usages* that define expert collaboration in different application domains (e.g. construction), which, in their turn, are believed to rely on extensive usage of services (Demirkan et al. 2008).

Another important challenge is the problem of *sustainable development*. In our analysis, we address the complexity of sustainability problem without specifying its partial aspects (e.g. environmental). By making a parallel between the phenomenon of sustainability of services and coherent knowledge formalizing, we formally define *sustainable services*, which we envisage as services that are capable to adapt to their environment, to dynamically integrate the ever-changing conditions of the environment, and as such to be sustainably coherent with its evolving challenges (Yurchyshyna & Opprecht, 2010).

This paper presents our approach for formalizing expert knowledge in construction by integrating new challenges of our society and by enriching the initial approach with sustainable services.

In next section, we discuss some related work concerning the problem of knowledge formalization in construction. In section 3, we develop our services-based approach for formalizing expert knowledge by introducing the information kernel and show how such knowledge actionalizing contributes to the development of sustainable services. Section 4 briefly describes a conceptual methodology for developing a cross-pollination space for construction. In conclusion, we discuss the scope of the ongoing work from the scientific point of view, as well as its possible application in the construction industry.

2 ONTOLOGIES AND SUSTAINABLE SERVICES

The construction industry is regulated by the large amount of construction rules and regulations of different levels: municipal national, international, and types: acoustics, accessibility, etc.

In (Yurchyshyna et al. 2008), we briefly presented main approaches for intelligent representation of (i) construction projects; (ii) tacit expert knowledge; (iii) construction rules; and (iv) expert practices.

Another aspect of the development and usage of domain ontologies, i.e. handling different *user profiles*, is discussed in (Sutterer et al. 2008). Other works describe different methods for automatic creating and applying user profiles in information systems: (Golemati et al. 2007) that allows personalizing the application of such systems, (Yurchyshyna et al. 2009) aimed at contextualization of the acquired ontology by integrating the results of semantic search based on usage of this ontology, contextual information retrieval according to ontology-based profiles (Challam et al. 2007), to mention but a few.

By rethinking the problem of formalizing expert knowledge for construction, we base on services science (Wu & Olson, 2007), (Demirkan et al. 2008) and the added value required in the process of knowledge actionalizing (Argyris, 1996), (Cencioni & Bertolo, 2006).

Creativity aspects of idea and knowledge creation process have been currently studied in management (Nonaka et al. 2000) where creation is perceived as a dynamic process resulting usage, as well as in generic models of creative thinking (Plsek, 1997).

It is also remarkable that in the case of multidisciplinary domains it is indispensable to provide the tools that guarantee the semantic consistency of domain knowledge and its coherent interpretation for different application contexts (in construction, for example, there might be misunderstanding between electric engineers and conformity experts that use different professional jargon, but are referring to the same knowledge).

In this paper, we also try to include into our analysis a complementary problem of sustainable development that received a new dimension in the context of knowledge- and services-oriented society. In other words, we analyse general criteria for sustainable development introduced in (Pezzey & Toman, 2002), and further discussed in (Spangenberg, 2005), (Olla, 2008), the factors defining sustainable services and their excellence (Chen et al. 2008), and role of sustainable services in innovation (Barafort & Rousseau, 2009). These and other works lead us to conclude on the interdependence of cognitive aspects of ontology-based knowledge, which is created, exchanged and adapted thanks to services, and its influence on sustainable development of a system/service that dynamically adapts to its evolving environment (Yurchyshyna & Opprecht, 2010).

A more detailed review of our current works can be found in (Yurchyshyna et al. 2008), (Yurchyshyna & Léonard, 2009), (Yurchyshyna & Zarli, 2009), Yurchyshyna et al. 2009), (Léonard & Yurchyshyna, 2010), and (Yurchyshyna & Opprecht, 2010).

3 TOWARDS IMPROVING FORMALIZING EXPERT KNOWLEDGE

Inspired by the recent development of the services science (Demirkan, 2008) and the new possibilities it might bring to the problem of knowledge formalizing, our current research is held under the services-based vision. In order to model expert domain knowledge, we introduce a services-based approach that relies on the information kernel, which is dynamically constructed thanks to the knowledge actionalizing process. We consequently show how the process of such knowledge actionalizing contributes to the development of sustainable services.

3.1 *Information kernel*

To concretize our definition of the information kernel (Yurchyshyna & Léonard, 2009), we first extend the semantics of ontologies, which we envisage as various knowledge bases that: (i) allow the formal representation of mandatory (for the specific task) knowledge; (ii) contain non contradictory knowledge shared by all experts and accepted by users; (iii) are characterised by sustainable knowledge that can not be doubted during the development of information systems and their functioning.

In the context of knowledge formalizing, the information kernel is developed as a conceptual model of the exchanged knowledge (Yurchyshyna & Opprecht, 2010). It concretizes the semantics of services involved in the process of knowledge formalizing and is based on shared concepts, roles, business rules and integrity constraints of the service. Its aim is thus to seamlessly connect the level of domain ontologies with the level of concrete implementation, and to ensure the coherence of all service activities.

The information kernel is developed thanks to the process of knowledge actionalizing (Argyris, 1996), (Cencioni & Bertolo, 2006). During this process (Fig. 1), the initial knowledge of domain ontologies is transferred to the information kernel where it is discussed and shared by domain experts.

The shared knowledge from the ontological level that might be useful for implementation by services is then actionalized. In other words, we detail the scope of the domain knowledge to be formalized in form of key concepts, relationships between them and the ontological rules, in order to be used in the specific implementation.

The results of the implementation of services and the semantics of the usage of concepts and relationships of the information kernel are then analyzed. We check if the knowledge acquired from the usage is shareable by all elements of the initial ontologies, transform it in shared concepts and integrate it into the information kernel.

Finally, this knowledge, which is validated by usage, can be integrated into initial ontologies, as well as to services related to actionalizing the knowledge, in order to dynamically update the information kernel, according to the process of formalization and usage of expert domain knowledge.

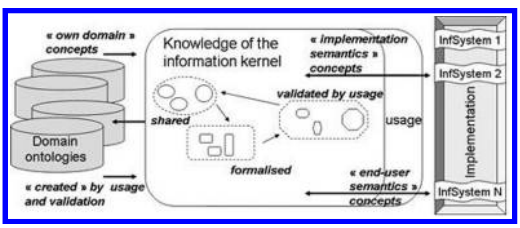

Figure 1. Information kernel: Formalization and validation of domain knowledge.

3.2 *Services: From usage-based validation to creativity*

In the previous section, we illustrated how knowledge actionalizing contributes to the dynamic construction of the information kernel.

It is important to underline that this process of knowledge actionalizing leads to a double result. On one hand, the shared knowledge acquired in the process of actionalizing guarantees the semantic consistency of initial domain ontologies and various services/systems at the implementation level, which is validated by their usage. From another hand, the process of actionalizing contributes to value co-creation.

Indeed, the process of identification of shared knowledge by different experts allows them not only to enrich their own understanding and to identify the added value of knowledge, which is capitalized from their collaboration, but also the process of knowledge actionalizing contributes to the enrichment of situations of its usage. The collaboration of various experts during the development of the information kernel, which is followed by the integration of the results of its usage, as well as expert negotiations create new situations where this knowledge *might* be used, and therefore, the situations where users *might* actionalize this knowledge. Technically, it means that the domain ontology is constantly enriched by new integrity rules that are dynamically executed in the process of the usage of services; that, in its turn, leads to the creative development of shared semantic environment (Fig. 2).

Our methodology of knowledge actionalizing is based on and enabled by different types of services: (i) enabling knowledge formalization;

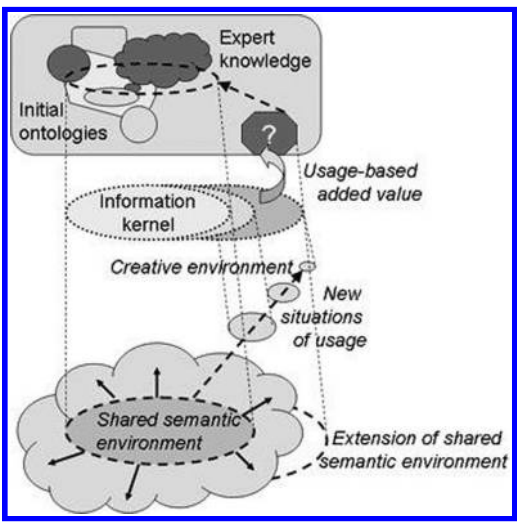

Figure 2. Extension of shared semantic environment.

(ii) identifying shared concepts and relationships; (iii) acquiring and interpreting the results of usage; (iv) checking the consistency of the information kernel; (v) facilitating collaboration, to mention but a few.

In other words, the process of knowledge actionalizing leads to the construction of the environment that motivates creativity and gives the necessary tools for its dynamic development. We argue thus that services become the key element for knowledge value creation that is achieved by actionalizing the knowledge related to corresponding domain ontologies by its usage.

3.3 *When services become sustainable*

The conclusions of the previous section on services as both the tools and the environment of co-creation and usage have an important theoretical implication.

Our work on the development of an ontology- and services-based approach for developing the information kernel allows us to demonstrate the impact of the information kernel to sustainable development of services. In fact, it allows us to identify some important aspects that can be envisaged as classifying characteristics for defining a sustainable service; and as such, to propose a formal approach for defining sustainable services.

Our definition of a sustainable service (Yurchyshyna & Opprecht, 2010) comprises 5 main characteristics:

- It is a service capable to adapt to its environment, to *dynamically* integrate the *ever-changing* conditions of this *environment*, and as such to be sustainably coherent with its evolving challenges.
- It is dynamically built thanks to its *information kernel* that relies on domain, legal and knowledge ontologies and *defines the semantics* of services.
- It allows *capitalizing tacit knowledge* related to the usage of services.
- It guarantees the *validation by practices of usage*, and as such helps to identify new semantics to be integrated into the information kernel.
- A sustainable service is based on *ontologies*, formalized as knowledge bases, and non-formalized expert knowledge, as well as trans-disciplinary common practices.

A sustainable service is, thus, defined by construction, according to the main characteristics of a service taking part in the process of knowledge actionalizing. The proposed definition is only one of its possible definitions: we do not claim its completeness and/or uniqueness, but underline the necessity of the further research on its enrichment.

In fact, this allows us to conclude on the interdependence between the process of knowledge actionalizing by developing the information kernel and the phenomenon of services sustainability. Such definition of sustainability by construction is based on the unique ability of services to serve both the tools and the environment for co-creation and usage. As such, they guarantee the coherent development of the corresponding systems, as well as the dynamic integration of the usage-based knowledge into initial construction-related ontologies that contributes to the general enrichment and modelability of the complex and multi-disciplinary construction domain.

4 CROSS-POLLINATION SPACE FOR CONSTRUCTION

The described methodology for capitalizing expert knowledge by its actionalizing with the help of the information kernel can be practically implemented as the so called Cross-Pollination Space (CPS).

The development of the generic CPS is our current work, and its detailed description can be found in (Léonard & Yurchyshyna, 2010), (Yurchyshyna & Opprecht, 2010). In the context of this article, to clarify a general understanding, we briefly describe its conceptual framework and discuss a possible use case to be applicable in the construction domain.

4.1 *Conceptual framework of CPS*

Generally speaking, the cross-pollination space, CPS, is a platform for enabling the creation of new domain services that is based on the analysis of the existing and retrieved knowledge of the domain.

CPS aims to support collective, trans-disciplinary and co-creative activities for the generation of ideas, and particularly the innovation phases of a service lifecycle based on knowledge. CPS functioning is based on the three keystones of our conceptual model for exchanged knowledge (cf. Section 3.1): (i) information kernel, (ii) domain ontologies (formalized and non-formalized knowledge bases), and (iii) services allowing identification and integration of actionable knowledge, thanks to validation by usage.

The CPS conceptual framework is based on the services approach: services are dynamically used for capturing main concepts of each domain, elaborating the cognitive information, capitalizing the results of its implementation and usage, as well as assisting the process of negotiation and collaboration corresponding to identifying the semantics of knowledge used by different experts.

For example, in construction, one distinguishes different semantics of the same concepts used by an electrical engineer, an architect, a compliance expert, etc.

The conceptual framework of a construction-related CPS is provided at Fig. 3. It represents the improved adaptation of the generic CPS discussed in (Léonard & Yurchyshyna, 2010).

The main components of the construction-related CPS are developed to support the three levels of the exchange knowledge (i.e. the information kernel, the level of ontologies, the corresponding services). They are as follows: (i) CPS communication interface that allows acquiring domain knowledge (both formalized and non) and transferring the shared knowledge of the validated information kernel; (ii) CPS formalization module that aims to develop a formal representation of construction-related expert knowledge coming from trans-disciplinary domains; (iii) CPS reasoning module aimed to process this knowledge by applying complex ontological and integrity rules; (iv) module for knowledge organization and scheduling that integrates common practices in applying validated expert knowledge; and (v) CPS result generator that formally synthesizes the acquired actionable knowledge and defines the module of knowledge to be used for service creation.

As the result of its functioning, CPS allows creating a formal representation of construction-related knowledge that is shared and validated by different construction experts, is semantically coherent and corresponds to the dynamic usage. Thanks to its trans-disciplinarity and complexity, this knowledge creates the environment for innovation in the construction domain and represents the main tool for developing new services, which become sustainable by construction.

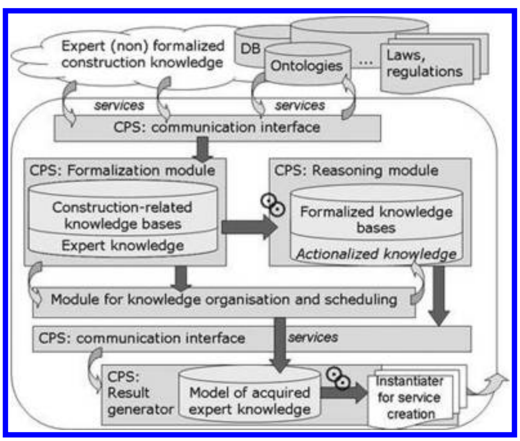

Figure 3. Cross-pollination space for construction-related idea development.

4.2 *Use case of CPS for construction: Design of a building conform to construction norms*

A possible usage scenario of the development of construction-oriented CPS can be drawn around the problem of designing a building that would be conforming to construction norms and regulations.

The complexity of this problem requires the collaboration of various experts: an architect, engineers specialized in different fields (e.g. thermal, electric, resistance, etc.), a specialist in regulation texts, a checking expert, etc.—which joint aim is to develop a coherent model of a building conforming to a selected set of construction norms. It is obvious that one of the key tasks of their work is to achieve the shared understanding of all the details, mandatory for such development.

Their mutual communication leads to defining the knowledge that concretizes the semantics of the concept of a *conforming building*, and, as a result, to developing the information kernel of this notion. It can be achieved, for example, by expliciting some knowledge (e.g. an electric engineer concretizes which exactly characteristics guarantee the conformity of a building to construction norms), by understanding this knowledge by other experts and by formalizing it. This formalized knowledge can thus be added to the model of a *conforming building*.

In some cases, however, the formalized knowledge might turn out semantically vague and require correction for specific implementations. For example, let us imagine the situation when the initial shared understanding of the concept of *accessible entrance* is defined by an architect through the concept of door, and is shared by other experts. The model of a *conforming building* is thus defined by the concept of a *door*. This actionable knowledge is then used for developing a service that identifies, which buildings are conforming. In a particular case of a building with an entrance defined by different construction elements (a composed *arch*, for example), this building will be classified as non-conforming, due to absence of a conforming *door*. In other words, the implementation allows one to identify the non-coherency of the semantics of the actionable knowledge, so the information kernel should be dynamically updated, according to this usage-based knowledge.

Practically it means that the usage-based knowledge "*entrance can be defined by an arch*" is transferred to CPS where construction experts collaborate to update the semantics of an *entrance* and a *conforming building*. Once shared and validated, these concepts can consequently be added to initial knowledge bases: e.g. by enlarging the formal ontological definition of the *door* concept in buildingSMART ontology (IFD, 2010) or redefining the concept of a *conforming building* in specific local ontologies.

A complimentary consequence of CPS functioning is the identification the situations of usage where the regulation texts should be reformulated and corrected, in order to avoid ambiguity. For example, in different situations of usage, it might become necessary to formally define the concept of an *entrance* with and without *stairs*, as they lead to different situations of usage, different types of knowledge to be taken into account, and as the result, create different environments. Such implementation and validation by usage empowered by services serve, thus, as a tool for knowledge actionalizing, and are one of the main leverages for its sustainable creation.

5 CONCLUSIONS AND PERSPECTIVES

This paper discusses our ontologies- and services-based approach for formalizing expert knowledge in construction, by integrating new challenges and by enriching our initial approach for capitalizing expert knowledge with sustainable services.

In order to study its feasibility for the construction domain, we developed a conceptual framework of the cross-pollination space aimed to capitalize construction expert knowledge for the development of sustainable services. We also illustrated this approach by a simplified usage scenario that shows the creation and validation of this knowledge.

The complexity of this research opens a large range for possible perspectives. First, this is our ongoing work, and the further improvement and enrichment of the conceptual methodology are to be achieved from its practical implementation. Second, we are particularly interested in modelling the creativity aspects characterizing CPS functioning. Third, we are currently working on further formalization of the definition of sustainable services. Finally, despite promisingly encouraging generic investigations, it is, however, a real challenge to contextualize the developed approach for a practical—very complex—construction domain.

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A concept of automated building based on BIM, nano- and biotechnology

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ABSTRACT: Fully automated building is a dream of many engineers and architects, and has been a motivation for various systems, which are able to automatically build even large or complex parts, but not an entire building with all its subsystems. In the paper we are presenting a concept of a fully automated building system, which resides on bio and nanotechnology and on a complete digital product model. One of the main objectives of our project was to formulate requirements, which would stimulate further interdisciplinary top-down and bottom-up research that will help the construction industry to reach the ultimate goal, the fully automated nano- to meter-scale building.

1 INTRODUCTION

1.1 *Automated building*

The construction process is complex and buildings are of large size, which is both a significant obstacle for automation. Prefabrication is still the dominant way of automation in construction, but new concepts and technologies are already being developed. Huang (2005) listed most of them in his thesis where in most examples specialized robots perform specific activities in the building process (for example concrete floor finishing). One that utilizes the great potential of automated construction of whole structures as well as components is Contour Crafting (Khoshnevis 2004). Rapid prototype engineering is another approach, which covers the building as a whole, and is therefore closely linked to a digital 3D model of a building.

Shiro studio printed a 3 × 3 m model of a pavilion using a new robotic building system d_shape (Radiolaria 2009). The material is produced using binder, which transforms any kind of sand into a marble-like material (i.e. a mineral with microcrystalline characteristics) and with a resistance and traction much superior to Portland Cement, so much so that there is no need to use iron to reinforce the structure. d_shape products are limited to 6 × 6 m cube. Another attempt of automated production has been developed at University of Southern California's Center for Rapid Automated Fabrication Technologies. Concrete and gypsum are used as the basic material. Strain gauges and other components can be embedded within walls to vary the composition of structures by layering in different materials during construction. Metal reinforcement, plumbing, electrical systems, and tiling can also be automated (Bowen 2007). Both systems use sophisticated equipment for production and need the building material to be transported to the building site in a conventional way. They do, however, represent an important contribution to more efficient, automated building.

1.2 *Nano and biotechnology*

Nanotechnology is the study of the control of matter on an atomic and molecular scale. It has the potential to create new materials and devices with applications in medicine, electronics, energy production, but also construction. Many works are giving good overview of nanotechnology (e.g. Peterson 2004, Regis 1995, Krummenacker & Lewis 1995), but the origin of this encompassing field is often attributed to Richard Feynman and his now legendary talk "There's Plenty of Room at the Bottom" (Feynman 1960) where Feynman laid bare both the potentials and challenges of developing nano-scale technology.

Since the discovery of carbon nanotubes in the early 1990s (Iijima 1991) there has been a concerted effort to both characterize and control nanotube properties through careful preparation during synthesis. The predicted properties of atomically precise carbon nanotubes would lend themselves well to a wide range of applications in electronics, thermoelectric and structural materials, and while commercial quantities of defect-free tubes are not yet available, carbon nanotubes are beginning to find use in materials today (Fifield 2007).

The impressive properties of carbon nanotubes make them especially appealing in use as structural and mechanical materials. The tensile strength of carbon nanotubes has been measured to be in the

10 s of GPa with a Young's modulus on the order of a TPa (Fifield 2007). Carbon nanotubes have been shown to be chemically stable due to their unique geometric structure (Kuzumaki 2000). The increased use of carbon nanotubes in commercial applications will depend heavily on better production methods with an emphasis on the control of physical properties and producing bulk quantities. However carbon nanotubes are currently being employed in a wide range of nano-materials today. Many of these materials are composite materials created by combining carbon nanotubes with other more conventional structural materials to enhance strength and other performance-related characteristics.

Nanorobotics is an emerging field of nanotechnology that deals with the controlled manipulation of nano-scale objects (Requicha 2003). So far interactions with atomic—and molecular-sized objects are based on several approaches. Industrial nanorobotics is using complex microscopes (strategies of nanomanipulation under various microscopes is shown in (Fukuda et al. 2009)) to control and sense nanomanipulation.

Bio-nanorobotics is focused on bio-inspired mechanisms, actuators, sensors and robots evolving in biological environments (Wang 2009), inventing new design methods and tools (Hamdi et al. 2007). Molecular biomimetic is an emerging field in which hybrid technologies are developed by using the tools of molecular biology and nanotechnology. Polypeptides can now be genetically engineered to specifically bind to selected inorganic compounds for applications in nano- and biotechnology (Sarikaya et al. 2003). This approach is seen as very promising in the near future as we are learning from nature to design highly efficient and powerful artificial nanomachines for complex operations in diverse realistic environments, leading to practical nanoscale applications in the not so distant future (Wang 2009). Currently, bio-nanorobotics development is closest to application in medicine (Cavalcanti et al. 2009, Martel et al. 2009).

According to the Nanoforum report: Nanotechnology and Construction (Mann 2006), so far the use of nanotechnology in construction has been in enhancing the characteristics of construction materials, including concrete, steel, coatings and glass, leading to low maintenance windows, long lasting scratch resistant floors, super strong structural components, improved longer lasting facade paint, self-cleaning facades and windows, antimicrobial steel surfaces, improved industrial building maintenance, lower energy consuming buildings, longer lasting constructions.

Biotechnology refers to using organisms or biological substances to solve problems and make useful products. Technology by itself is not something new and biotechnological products and processes are intentionally used for millenniums, even more, we can say that our civilization depends on biotechnology. In narrow terms we can recognize biotechnology in ancient procedures as using yeasts in brewing beer or raising bread, and microorganisms in numerous fermentations of milk. In broader terms agriculture is a fine example of biotechnology where plants are used to produce something useful, like drugs, food, fuels, building materials, etc.

Organisms used in biotechnological processes are only rarely used in original forms. More often their genome was altered toward better yields, improved quality of products, physical properties, etc. Before the era of genetic engineering processes like selection, crossing or induced mutations to produce new genes or combinations of them were used. All these processes are time consuming and depend on chance and good luck, with additional barrier to combine genes from unrelated organisms, which are reproductively isolated from each other. Many of the barriers are nowadays routinely crossed using tools from genetic engineering to modify existing genes of single organism or transfer genes between organisms. Nowadays organisms like bacteria Escherichia coli producing insulin (Tavassoli 2010) or herbicide tolerant crops (Knezevic 2007) are in commercial use and new genetic modified organisms are in testing phases or foreseen to be introduced in commercial use.

2 AUTOMATED NANO TO METER-SCALE BUILDING

2.1 *Concept*

A top-down concept has been developed following certain suppositions, which are closely related to our motivation to reduce waste, pollution and energy consumption caused by traditional building technologies. The first supposition therefore was to use materials that exists on site and can be transformed into building materials at the nano level. As discussed in the previous section, carbon nanotubes have extraordinary characteristics, which can be varied using today's production nanotechnologies. The next supposition, therefore, was to use carbon as the basic material. As carbon exists in nature in vast amounts, the next supposition was to extract it from CO_2 from the air. The building process is to be executed on the nano level using active nano devices that shall be controlled extrinsically using a detailed Building Information Model (BIM) as the source of all necessary information.

The fundamental building process is taking part at nano level by multifunctional nanodevices (nanorobots), which are capable of capturing CO_2

from the air and extracting C molecules from it, releasing O_2 back into the air, and building 3D carbon nanotube arrays with characteristics required for a specific area (strength, conductivity, color, transparency etc.) Nanorobots are controlled and powered externally by light; instructions are coded using specific wavelengths. Light is emitted by a projector installed above the site (Fig. 1). To avoid interference with light emitted by other sources, an adequate wavelength spectrum has to be chosen. The projector is using the detailed BIM model as input, and transmits continuously the horizontal cross-section, going from the bottom to the top height of the model. Openings of the final model are temporarily filled with carbon nanomaterial, which transforms back into CO_2 after a specific time period (or under specific conditions), when its function as a supporting structure is fulfilled. All utilities and coatings (if necessary) are built at the same time, together with the bearing structure (e.g. pipelines, power lines, communication lines), and are part of the building (see Fig. 1).

2.2 *The process*

The building process starts with designing a detailed BIM model with all necessary utilities and coatings, as well as temporary fillings, which can be added automatically after the building model is finished, by following the rule that every part of the structure has to be vertically supported down to the base level. Site preparation is the next step and includes excavation and projector installation. It is followed by deploying nanorobots onto the maximal extent of the building layout. The site is now ready and the automated construction starts by continuously emitting instructions represented as specific light wavelengths to build 3D CNT arrays with required characteristics, until the top of the building is reached. After the light is off for a certain time, the nanorobots stop to function permanently, thus preventing any unwanted activity after the process is finished.

The load bearing material is in function instantly, therefore the temporary supporting material can dissolve after the building is finished. It disappears off the building in the form of CO_2 gas (e.g. from rooms, niches, pipelines and any other volumes designed empty). With this the building is finished. With transparent CNT even windows could be "built-in" during the process, as well as some further equipment. It is, however, too early to explore in such detail all the effects of nano- to meter-scale building.

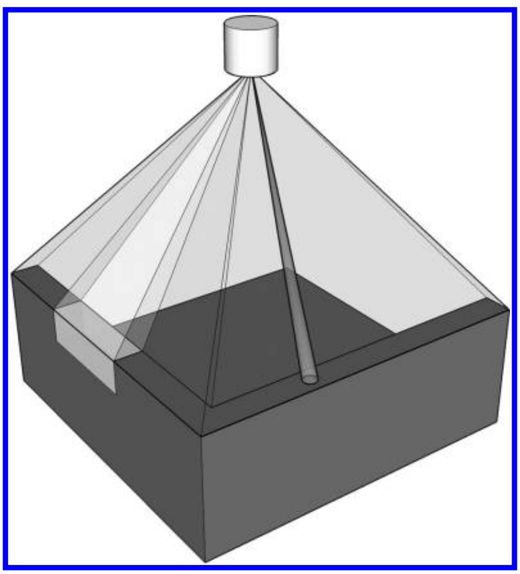

Figure 1. Nano- to meter-scale building using light projector to send information to bionanorobots on the building plane.

2.3 *Nanomaterial and bionanorobots*

Carbon nanotubes possess many of the properties one would choose in designing an ideal structural material. They have a very high strength to weight ratio, are stable and inert at a wide range of temperatures, and can have varying degrees of conductivity based on their geometric properties. However, one challenge in utilizing carbon nanotubes in meter-scale building is finding a natural configuration of nanotubes that allows for unlimited assembly in all three spatial dimensions while retaining the afore mentioned properties. One very promising family of configurations can be found in Schwarzite structures, named so in honor of the mathematician H.A. Schwarz who first explored similar triply periodic minimal surfaces (Lenosky et al. 1992).

To get a rough comparison with traditional building we've estimated the embodied energy for both approaches. Regarding traditional building Suzuki et al. (1995) calculated energy consumption for construction as 8–10 GJ per square meter of floor area for multi-family steel reinforced concrete houses, 3 GJ for wooden single-family houses, and 4.5 GJ for lightweight steel structure single-family houses. CO_2 emission resulting from construction is 850, 250 and 400 kg/m^2, respectively. The energy required to obtain carbon from the atmosphere sufficient to synthesize one cubic meter of a required Schwarzite material is approximately 3.6 GJ. To compare with the required energy used for traditional building we need to estimate the ratio between floor area of the building and the volume of the material built into it.

In traditional building this ratio is between 1 and 2, but for a CNT construction it can be estimated at least 3 as its load capacity is much higher. In this case the energy consumption for a square meter of a building build of 3D CNT array material would be around 1 GJ.

For the extrinsically controlled nano- to meter-scale building process presented above the bio-nanorobots would have to be able to recognize different wavelengths and compile them into instructions, transform light energy into working energy, extract CO_2 molecules from the air and decompose them into C and O_2, and build 3D CNT array using C molecules. According to the current state in biotechnology we can optimistically search for engineering modules produced for different purposes in developing fields of synthetic biology and biotechnology to assemble them in a new sequence with a functional building as the end product.

3 BUILDING INFORMATION MODEL (BIM) AND NANO- TO METER-SCALE BUILDING EQUIPMENT

In the nano- to meter-scale building process the main activity is to design a detailed digital model of the building. BIM technology of today, including detailed 3D geometry and material properties, does already fit the requirements of nano—to meter-scale building. There are, however, some specific demands. Due to the high load bearing capacity of the used nanomaterial there is no need for rebar or other load bearing reinforcements. The structure is therefore homogeneous, and construction elements (beams, columns, walls etc.) have to be merged into a single structure, as they will be built in one step. All utilities have to be designed within the complete BIM in final details as they will be built together in a single step.

After the design process is finished and the model checked the model has to be prepared for the production phase. All systems of the building included within the Building Information Model become solid volumes with specific characteristics (conductivity, transparency, insulation, etc.). After this step, which can be automated, temporary supporting material has to be filled in all parts of the building, where any part of the structure exist on a higher vertical level (rooms, niches, pipes etc.).

Existing BIM modelers can be extended with special functionality to fulfill these requirements, including the filling of temporary supporting material, which can be generated automatically as it follows a very simple rule (it fills every empty space below any part of the designed building). Utility design can be supported with parametric functions, which allow input of required characteristics of electrical wiring, water pipelines, etc., with post-processors that create the final detailed geometrical design. Complete BIMs (product models) will, however, need to become much better integrated than today. As well as modelers intended for various subsystems of the building.

The design process will not have to undergo any dramatic changes, except that it will have to be more collaborative and much more accurate. However, small size models could be produced quickly and automatically for review and error checking.

The equipment that is to be used for the extrinsic control of the nano- to meter-scale building process consists of a light projector with a reliable power supply and stable geometrical position, which is crucial for achieving the desired precision of all details of the building. The projector also has to have a built-in computer that controls the light projection and thus the whole process of nano- to meter-scale building. It is connected to another computer on site, which is used to input data (transmit the BIM to the projector) and to monitor the process. No other equipment is required.

4 CONCLUSIONS

We are aware that the presented nano- to meter scale building is a concept that will need many years of intensive research in the areas of biotechnology (bionanorobots), nanomaterials (3D CNT array), physics (light projector) and construction informatics, before some useful results can be expected. There do, however, exist other concepts of building automation (see introduction), which will require a similar, much higher level of integrated Building Information Models, much earlier. We can expect earlier intermediate results in our approach too, e.g. bionanorobots producing building material based on cellulose. Thus the need for a complete and fully integrated Building Information Model is becoming a necessity.

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Novel construction processes using Additive Layer Manufacturing

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ABSTRACT: There is a general consent on the limited usage of digital technologies in construction which has caused considerable delays in terms of commercial impact if compared to other rival sectors. Numerical control for an automated construction directly from digital models has now become more and more possible, as Additive Layer Manufacturing (ALM) processes which generate geometrically complex physical objects from digital 3D models is being used for production of prototypes in many industrial sectors such as medical, automotive, aerospace, household products and many architecture bureaus. On the other hand, there are few cases where the construction industry has seen introduction of ALM as a solution to produce optimised structures for which few examples can be given but again limited to research or art applications. The design and build optimisation aspect which is an essential element of the ALM is in many cases inspired from naturally existing organic systems for which the production of the object is only made possible by the capabilities of the ALM solution to generate complex geometries for free. Also the late rise in awareness of its potentials among the construction and built environment community and the increased pressure and the need for geometrically optimised built environment in regards of minimising the environmental impacts has rendered its implementation imminent. In this paper a review of existing applications of Additive Layer Manufacturing (ALM) for production of the few objects in construction and built environment is summarised. A case study is given to illustrate this technology's potential capabilities, the different methodologies which could be used and the chronological developments which may unfold when using ALM to simplify and speed up the transition from a novel idea to an exploitable process or component in construction. Consequently, the most important outcome which must be sought from this review and analysis is that the construction industry is lagging behind in adopting the digital technologies.

1 INTRODUCTION

The work reported in this paper is carried out within a European project entitled: "Industrialised, Integrated and Intelligent Construction (I3CON)", aiming to enable transformation toward sustainable construction industry, delivering industrially produced, integrated processes and intelligent buildings. It also supports the efforts toward the FreeForm mega scale construction challenge, where building components could be fabricated in-situ by processes directly from 3D digital data using Additive Layer Manufacturing (ALM) processes as a novel production methodology for construction in general. A new methodology for design, development and fabrication of an integrated Building Services (BS) system is therefore proposed and described as a case study, it comes in time to complement and push forwards the frontiers of digital construction. The novel methodology will bring together all the services in minimal proximal distances into a single trunking. This can be achieved through Computer Aided Design (CAD), novel mathematical manipulations and implementation of ALM.

ALM which is the enabling technology descried here for innovative structural and functional components is a direct production of finished goods using additive processing from digital data, which eliminates all tooling with design possibilities which are virtually limitless—rather than Design for Manufacture [1]. One of the principal advantages of ALM is the ability to manufacture working assemblies and linkages straight off the machine, which will lead in the future to the production of panel type constructions with fully embedded integrated utilities on site or in factory environment. In the reported case study this technology is used to enable the development of a Multi Service Trunking System (MSTS) that is based on nodes (spherical) and runs (elongated cylinders), and is designed while taking into consideration the currently applied building regulation and standards for BS including hot and cold water, hot and cold ventilation, electricity and data. Transition from conventional method of delivering and distributing services within a building to a novel smart design using complex geometry was a result of a mathematical conversion of linear tubular scattered system to an integrated, harmonised and parameterised model based on 3D surfaces.

2 PRIOR ART AND DEDUCTIONS

The prior art review which we have conducted was aimed to reveal the current applications of ALM within the construction industry and discovering if BS were integrated in any manner prior to this research work.

Competition for projects in construction sector concentrate on cost, where the cheapest bid wins and there is little time, money or energy to invest in innovation. The industry is also conservative and innovations only generate incremental changes [2]. There is also a growing skills shortage and the industry is likely to face increasing pressures from developing environmental issues [3]. The UK government has been addressing these issues through a succession of initiatives, prompted by the Latham and Egan reports [4–5]. The drive is towards leaner, better Modern Methods of Construction [6], which undoubtedly can be reinforced by serious uptake of physical integration at every level of the construction processes from design all the way through construction to usage. Bemtgen [7] proposed a detailed approach to transit from conceptual integration to physical integration. Starting by innovative planning & architecture then choosing Low-E materials, innovative components, take advantage of the Innovation in Building Management Systems (BMS) including monitoring to finally succeed in physical Integration of Renewable self supply.

A good example of Physical Integration (PI) encountered in construction sector is related to energy efficiency of the building. There is a revolution in large scale integration of renewable energy sources with other building structural components. As an example the integration of Photovoltaic (PV) into building facades and roof structures which is expected to provide a significant contribution to electricity generation Bahaj [8]. In essence of his method is a combination of the mature tiles industry, with state of the art plastic and photovoltaic technology as a good step towards physical and functional integration.

To promote the PI of functional and structural components the most important developments in the construction industry is the digital fabrication. The Vila Olimpica in Barcelona (1989–92), Spain is a good example to illustrate this [9]. It was designed by Frank Gehry [10] and constructed by Permasteelisa [11]. Designed using CATIA, which is a solid modelling tool that was originally made for the aerospace industry. The use of CNC technologies to produce art/architectural pieces is also exemplified by the work of Objectile, Paris [12], combining engineering, mathematics, technology, and philosophy to work on the industrial design and manufacturing of curved and variable forms of every proportion. The construction industry is becoming familiar with Digital Fabrication. Leading designers such as Buro Happold (London, UK) are using solid modelling tools to resolve freeform architectural surfaces into efficient, buildable structures. Rapid Prototyping is finding its place in the design process: Foster and Partners (London, UK) have a suite of modelling equipment that includes CNC laser cutting tools and a 3D printing process; 3D model production bureau's such as Slovinova (Hampshire, UK) [13], specialise in producing 3D architectural models. Gehry Technologies have developed their 'Digital Project' software, based on CATIA. Today Construction is using CAD/CAM to liberate architectural possibilities and all indications are that a new era of digital design is on the horizon.

An investigation conducted by Marsh [14] has showed that the Danish construction industrial transformation needed to focus on integrating BS technologies in the buildings of the future. Historically across many parts of the world [15] there has been a large growth in the extent and costs of BSs over the last 100 years due to changes in social and technological development [16]. This is because the perceptions of buildings are changing from static and passive constructions to dynamic and adaptable functional spaces. In this process, intelligent BSs [17–18] are becoming the driving force in meeting users' changing functional requirements over time. Consequently new strategic design principles can be developed to integrate and distribute the expanding range of BSs into buildings, so that changing user demands for new intelligent BSs technologies can be incorporated into the building design and procurement process. Also the largest productivity gains from industrialisation [19–20] can be achieved by focusing on BSs because they represent both a growing proportion of total construction costs, and the least industrialised part of the construction process. The national building survey by Amory Lovins concluded that: "A lack of integration in the design process has made buildings costlier to build, costlier to cool, and less comfortable than they should be." This situation remains true today, especially for HVAC systems that are being imposed on buildings rather than integrated into them [21–22].

As a whole, integration in buildings is to date limited to the control and the operational aspects while very little development was carried out on physically integrating parts and component forming buildings. We have therefore engaged into the development of a solution for integrating BSs using CAD surface and solid modelling tools with the support of the ALM technology aiming for a sustainability solution, reduction in energy wastage, gain in material usage and reduction in labour cost at various levels as described in this paper. The aim of this research is to address the challenge of physical integration of building services in a single trunking system and demonstrate through the multi services trunking system (MSTS) solution how one can develop and test virtually any complex solution using CAD and ALM.

3 CASE STUDY

3.1 *Methodology*

The methodology followed to demonstrate how novel technologies such as ALM could enable complex physical and functional integration in building was through development of the Multi-Services Trunking System (MSTS). It starts by generating CAD design from the calculated results and the findings of reviewing the currently observed standards by UK construction industry and the physics study carried out.

The identified objectives to perform the described development begins by first defining the interactions between the utilities and the materials to be used to make the MSTS, this investigation takes into account the currently practised building regulations followed by performing a physics study to calculate the distances between the utilities once brought together in a bundle assembly to allow generation of the 3D CAD models. The intended utilities to be transported by the multi-services trunking system are water (hot and cold), power (12 volts, 240 volts), data (5 volts signal, optical signal, etc.) and air for ventilation (hot and cold). Once this is fulfilled an evaluation of the trunking solutions will be carried out and an installation protocol will follow. A range of probing components is embedded into the MSTS for communication with building operating systems together with informing on user's activity. The potential risks of the proximity between services should be identified together with possible solutions. The physical integration challenge is related to the currently used manufacturing methods in construction and the design practices by architects, designers, and service engineers, materials performance, safety and longevity. Some of the materials tested within the produced prototypes showed some degrees of limitation which required more effort, time and cost to address, however there are already some promising new materials being developed using nano technology engineered compositions which can be considered for the development of this integrated BSs components.

All designs and calculations were undertaken for a case study which is an open space office designed for twenty people. The following parameters were obtained by the calculations based on the currently applied standard regulations, of the United Kingdom where the Water Supply (Water Fittings) Regulations and their Schedules are Statutory Instruments (1999 No. 1148 and No. 1506) [23], the British Standards: BS6700, BS CR 1752 and BS EN 1505, BS 7671 and BS6231, together with the physics study based on Bernoulli's Theorem (Daniel Bernoulli 1700–1782) for flow-metering, D'Arcy (D'Arcy Thompson 1860–1948) on fluid flow and Fourier's Law of heat conduction [24–25]. For potable water proximities calculated under the standard BS6700, we have found that a 21 mm ID pipe has to be positioned at 300 mm away from any hot water pipe (flow & return). Calculations for ventilation under standard BS CR 1752 and BS EN 1505 suggested an 8 L/s/occupant of fresh air which will sum up for 20 people as a duct 436–483 mm ID when conventional flow rates are applied. For power under the standard BS 7671, BS6231, 15 kW, 240 volts single phase AC @ 60 Amps is needed to satisfy all personnel and equipment requirements of the open space office. And for data the category 8 (CAT8) cables which are a $4 \times 22/1$ AWG will be very adequate and will satisfy the needs for more digital applications in the future.

Initial attempts of integrating all the six building services within this research using outcome from these calculations resulted in few solutions bringing together all the utilities pipes, cables and ducts in a bundle form under various arrangements such as: on a flat surface see Figure 1, on the internal surface of square or rectangular duct or on the internal surface of cylindrical duct. As can be seen in Figure 1a these arrangements were made within the proximity distances calculated. However, although the proposed solutions seemed interesting they all had a common limitation; they

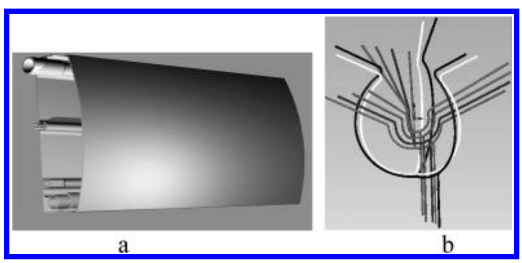

Figure 1. Initial solutions of 2D and 3D pipes distribution.

struggled to satisfy the proximity rules when distribution at nodal point is required. In other words there is not a solution which could allow the calculated distance to be respected if the number of distributions needed in *n* directions is superior to two (*n*>*2*) as can be seen from Figure 1b. Consequently, the distribution in more than two directions at nodal point has made these integration solutions impractical and unusable.

These solutions were in their core based on the conventional method of distributing services in a building which consist of a set of different curved routes (pipes, ducts or cables) for each of the services (such as hot and cold water, ventilation, electricity, data, gas, return water and waste water). These curved routes extend from the main point as the utility enter the building to the different location points where they are required within the building. To transit from this conventional way of thinking to a more advanced method, all the services are integrated in a manner to follow a set of routes bound to stay at a fixed distance from a single common optimised 3D curve while they distribute through out the building. This complex transition will involve passage from distribution in 2D to distribution in 3D.

3.2 *MSTS solution—CAD design*

The conventional scattered multi routes tubular distribution needed replacement by another geometrical form which will satisfy the integration of all the utilities in a single type of trunking in a radical manner to the initial solution given in the previous section. It is the Multi Service Trunking System (MSTS) that is based on nodes (spherical) and runs (elongated cylinders) which requires cubic Bezier surfaces [26] for linking spheres to cylinders to provide the unique geometrical solution for this integration.

A functional multi-services trunking run & node were first designed on the basis of a newly developed mathematical manipulation combined to information gathered from the standards review and the undertaken physics calculations. The designs were carried out in CAD using Rhino software, they were made as a succession of concentric shells (sphere and cylinder linked by Bezier surface) to house a series of empty concentric gaps as conduit for services or to be filled with insulating material or low melting alloys. The empty gaps will serve as channels for services in similar manner to pipes that are conventionally used for plumbing and ventilation. The node is particularly innovative as it guarantees distribution of services in all directions and in any number of directions, while runs are pustule to cross long distances to link the distribution nodes.

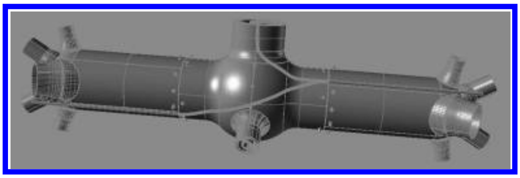

Figure 2. Optimised novel solutions—MSTS.

The CAD designed complex geometries as can be seen in Figure 2 could be produced by a combination of manufacturing technologies, a conventional to produce the runs directly by simple extrusion of any complex pattern while the most geometrically complex part which is the node will be produced by a novel manufacturing technique such as ALM.

The described approach which is the MSTS will relate all the utilities and services made available to a building in a very novel way. However to fulfil this a number of requirements need to be satisfied to successfully carry out development and produce a functional prototype for demonstration as given in figure 2. These requirements relate to the different components necessary to allow completion of the MSTS which will be made of vertical and horizontal trunking runs and distribution nodes onto which a network of sensors and actuators will be laid. These components will permit continuation of services to the next compartment of building while providing all the services as required at any point along the trunking system. The delivery and distribution specifications of runs and nodes will be designed in accordance to any user's requirements as the modelling will be made in CAD; there is always a possibility to adapt the size and the number of services for each and unique requirement.

A number of physical prototypes were produced for experimental purpose and for design improvement and refinement. Assessment of material requirements in terms of manufacturability and usability was also performed; few existing materials for ALM processes were tested and evaluated by producing different prototypes while improving the design and adding functionalities, these were specifically designed for Stereolithography systems, they were Accura 60 plastic and the WaterShed XC11122 [30]. Although full specifications were available from their data sheet they were further tested for the MSTS in regards of their mechanical properties, their thermal resistance and thermal insulation. A number of thermal insulation materials were also tested in regards of the way they improve the walls U-value and how they physically behave when forced into the narrow gaps between the shells of the MSTS. These were Cerafix Translucent Silicone Sealant and SylGuard Silicon 184. A low melting alloy was also filled around the spiral channels for data and this was the MCP 47 which has a low melting point of 47°C.

4 SUMMARY

As demonstrated in this paper an important change is about to happen to the way we make our habitats, these will be highly optimised and capable to induce environmental control only by evolving construction methods which utilise geometric form with the Freeform Construction technology making the new generation of homes become a reality [27]. Currently there are three systems under development or close to commercialisation in the UK, Italy and the USA. It is worth sitting them at this stage of the paper to put more emphasis on the importance of these novel technologies for boosting the construction industry, both economically and through modernisation. Each uses a different strategy to form full-scale structures. In the UK, the Threshold Deposition Device describes the way in which extruded paste rheology is exploited for shear thinning and shear thickening behaviour. The controls, drivers, the gantry, the pumps and even the material are all commercial products. Enrico Dini in Italy is commercialising the Monolite process, which deposits layers of particulate, ranging from sand to marble chips, onto which the deposition head selective jets a binder which may be cementitious or polymeric. This solution overcomes the problems of supports by printing into a powder bed, after which the part is extricated. The Italian designer, who also happens to be an architect, claims that designers will be able to construct 3D models of their designs (for arts or buildings). According to the inventor, this process is not just cheaper but it is four times faster than conventional building method. The final process, in this category is by Behrokh Khoshnevis at the University of Southern California in the USA. Termed contour crafting (CC), the process seeks a solution to selectively deposit material at 'bulk rate' whilst manipulating the deposited material with a trowel. Surface finishes are as good as a plasterer can achieve. Some of the important features of CC are high fabrication rates and the ability to use a wider choice of build materials [28–29]. Using thixotropic materials with rapid curing properties and low shrinkage characteristics, consecutive layers of wall structures can be built, by an incremental controlled of thickness.

5 CONCLUSION

It was foreseen that if these novel construction processes such ALM are adopted embedding all the utilities into a single trunking will lead to reduction in costs of the buildings of the future. The re-configurability, flexibility and adaptability of the building spaces to suit different users requirement at different stages of the building life is a major advantage if this solution is adopted. A direct reduction in the labour work and an important saving on energy and time of manufacturing, assembly and maintenance can also be claimed together with near zero wastage during the production process. The new system will be tested in regards of its ease and speed of installation as well as real cost in comparison with conventional systems. Tests may involve assessing performances as well as advantages in contrast with the conventional services delivery systems. Further research will be conducted to list all the utilities which can possibly benefit from the trunking system and to define the physical parameters and regulations that need to be considered in the design of the system.

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Advanced computing in engineering

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Developing a Knowledge Map for underground construction research projects

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ABSTRACT: While many tools for knowledge management for different scientific domains are being developed, the dynamic and unstructured nature of research projects makes the scientists are faced with problems such as information overload and vocabulary differences. A Knowledge map is a vital tool for solve vocabulary differences and improve knowledge management. Different approaches to knowledge maps in the construction domain are already created, but underground construction domain is still in the initial stages of development. Depending on the source and database, search terms may be different. Therefore, this paper presents a knowledge map for reusing researcher's tacit and explicit knowledge in the underground construction sub domain. To test the knowledge map, it is then implemented in a knowledge management system (SGAC- Active Knowledge Management System) developed to improve knowledge management in "The Multidimensional City" project, which is a multi-disciplinary research project that promotes the development and implementation of Spanish technological innovation in underground construction.

Keywords: Knowledge management, underground construction, knowledge map

1 INTRODUCTION

Research projects generate knowledge and innovation. In large-scale projects it is more difficult to organize and exchange information between project partners and to disseminate the results to the community of interest and other parties involved. In addition, it is difficult to share and disseminate information within a large project community due to the different sub-projects and tasks carried out by the research groups and companies involved.

Knowledge Management (KM) is the term given to the management of intangible assets that generate value for research groups, projects, organizations or research fields. Most of these intangibles are related to generating, capturing, structuring and transmitting information and knowledge. Therefore, it is important to define the way in which knowledge should be shared and disseminated in any type of research. Once knowledge has been generated and captured it must be structured so that other researchers and interested parties can obtain, reuse, and enhance it.

Although KM is not a new concept, it remains an emerging practice in the construction industry. Construction-related KM research covers areas such as setting KM parameters for construction entities (Kululanga & R. McCaffer, 2001), defining computer-assisted construction methods and knowledge (A. Udaipurwala & A.D. Russell, 2002), developing web-based acquisition of knowledge maps in construction KM (J-H. Woo, et al., 2004), developing an activity-based knowledge management system for contractors (H. Ping Tserng & Yu-Cheng Lin, 2004), selecting appropriate KM strategies(J.M. Kamaraet al., 2001), and assisting project managers responsible for overseeing KM initiatives (J. Liebowitz, & I. Megbolugbe, 2003).

The possibility of using KM in construction projects has been analyzed in research projects such as Know Biz (P.M. Carrillo et al., 2003), CSanD (M.M.A. Khalfan, 2003), Clever (J.M. Kamara, 2002), e-Cognos (C. Limaet al., 2002), Klicon (T.J. McCarthy, 2000), and Capricon (C.E. Udeaja et al., 2008). Most KM research in the construction industry focuses on architecture, engineering and construction (AEC) rather than on sharing and disseminating research results, and no research has been carried out for specific construction subsectors such as underground construction.

Owing to the rapid evolution of the knowledge industry, many techniques have been developed to help the construction of knowledge networks. A knowledge map that creates relationships among isolated knowledge and represents knowledge via a hierarchy structure is a knowledge representation type that is most valuable. A knowledge map can clarify vague knowledge, enabling users and learners to easily find desired knowledge. Recently, domain knowledge about construction management has received considerable attention. Underground construction is an important subdomain within construction management. When a comprehensive knowledge map for underground construction sub domain can be constructed, domain development matures and users improve their knowledge.

Although approaches have been used to develop knowledge maps, their usability for underground construction research projects is not proven.

The paper is organized as follows. Section 2 presents a review of literature in the knowledge management and underground construction management domains to collect and summarize information on knowledge maps. Section 3describes the data sources used for developing a knowledge map for construction underground subdomain. Section 4presents the development of knowledge maps for underground construction. Section 5presents the implementation of this knowledge map to a knowledge management system (SGAC- Active Knowledge Management System). Section 6 presents conclusions and future research directions.

2 BACKGROUND

2.1 *Knowledge management*

Knowledge has been described as the product of learning, which is personal to an individual or organization. Davenport and Prusak (1998) state that knowledge is "a fluid mix of framed experience, values, contextual information and expert insight". They also argue that KM is much more than technology and that knowledge is more than just data and information. Therefore, data can be considered as the foundation on which information and knowledge are created.

Knowledge can be defined as either tacit or explicit (Polanyi, 1967). Tacit knowledge is the personal and context-specific knowledge of an individual, whereas explicit knowledge can be codified, collected, stored and disseminated—it is not bound to a person and is predominantly data. Knowledge can be generated by different sources. Specifically, explicit knowledge can be captured from documents, reports, standards, specifications, drawings, films, specifications, contracts, etc. (S. Kivrak, et al., 2008). In contrast, tacit knowledge is mainly captured from experts involved in the project, such as colleagues, the experience of individual companies, and personal experiences. Several tools and strategies can be used to support the knowledge creation process, including face-to-face interactions, coaching and mentoring, brainstorming, meetings, e-mail, training, and communities of practice. The knowledge itself may include process records, problems faced, problems solved, expert suggestions, knowhow, innovation, and experience notes.

A survey carried out by S. Kivrak et al. (2008) showed that journal articles, conferences, meetings, and reports are the predominant sources of knowledge acquisition in construction projects and that the Internet, external knowledge brokers, and external events such as conferences, seminars and exhibitions are less commonly used.

The words explicit and tacit can be misleading because they imply exclusivity. However, explicit knowledge is "grounded" in and created by externalizing (visualization, articulation, or codification) tacit knowledge. Udeaja et al. (2008) state that tacit knowledge is transferred in day-to-day social interactions, but that this process can be triggered formally or informally in a project environment. Therefore, tacit knowledge is made explicit so that it can be shared by others to form the basis of new knowledge. In a research project, this process is carried out in the minutes of meetings, workshop presentations, conferences, etc. In contrast, explicit knowledge can be captured from within the project or from external sources and then combined, edited or processed to form more complex and systematic explicit knowledge. This new explicit knowledge is then disseminated among members of the project. Finally, explicit knowledge is converted into tacit knowledge which is applied in practical situations and forms the basis of new research projects.

Knowledge management is divided into four main processes: 1) knowledge capture, 2) knowledge sharing, 3) knowledge reuse; and 4) knowledge maintenance.

Knowledge capture encompasses: indentifying the types/categories of knowledge to be managed and locating the learning situations; representing (indexing, organizing and structuring knowledge into themed areas) knowledge in the standard of format specified; and validating knowledge to ensure the credence of captured knowledge. Most information and knowledge is acquired in an office environment while the research project is running. There are well-known knowledge organization systems such as taxonomy, thesaurus, ontology, knowledge Maps and metadata, most of which are designed to organize as many relevant topics as possible.

The basic aim of knowledge sharing is to provide the right knowledge to the right person at the right time. According to Markus et al. (2001), this process can be passive, such as publishing a newsletter or using a knowledge repository for users to browse, or active, such as using an electronic alert to send knowledge to those who require it. However, knowledge is also shared through face-to-face meetings in addition to Information and Communication Technology (ICT) systems.

The knowledge reuse process includes reapplying knowledge and adapting or integrating knowledge for innovative purposes.

Knowledge maintenance covers reviewing, correcting, updating and refining knowledge to keep it up to date, and preserving and removing obsolete knowledge from archives.

2.2 *Learning from research results and findings*

Transferring experience and research results is a difficult process that consists of transmitting the knowledge acquired by individuals to others who can benefit from it, within a complex social-organizational context. The end users of research project results are usually other researchers, organizations, research and development (R&D) departments, and academics.

When talking about learning two different learning paths should be defined: academic learning and business learning. Academic learning consists of transferring structured knowledge for a specific purpose, which could be to obtain a university degree or to carry out research. Business learning is the day-to-day learning process of working in a company and can be considered as the acquisition of knowledge from personal experience.

The inherent organizational and cultural characteristics of research projects create barriers to the learning and knowledge transfer processes, the most serious of which is competition, since most, in respect of organization culture and traditions create challenging barriers for learning and experience transfer.

The most important barrier is the competition owing to the fact that the majority of the researchers don't want to share their results until they are published, patented or the project is finished and they want to maintain their ownership.

There are several other problems that affect the knowledge management process: researchers working on large-scale projects often begin new sub-projects without submitting reports on their previous work due to time constraints; researchers are so busy with routine tasks that they do not have time to store and index knowledge; there are very few systematized, continuous learning process between projects due to the lack of efficient knowledge transfer; a lot of important knowledge resides in the minds of the individuals; many decisions are often not recorded or documented; research knowledge can take many forms, including experiences, best practices, lessons learned, drawings, documents, etc.; knowledge is often poorly organized; and research experience is often individual and incidental (A.M. Al-Ghassani, J.M. 2006).

3 KNOWLEDGE MAPS FOR UNDERGROUND CONSTRUCTION RESEARCH PROJECTS

3.1 *Knowledge map*

Several accepted methods exist for knowledge representation, including rules, frames, semantic networks, concept diagrams (concept mapping) and knowledge maps (knowledge mapping) (J-B. Yang, 2007).

Davenport and Prusak defined a knowledge map as a knowledge yellow pages or a cleverly constructed database (1998). Knowledge maps are created by transferring certain aspects of knowledge into a graphic form that is easily understandable by end-users. Therefore, knowledge maps are consciously designed communication mediums between map makers and map users (Wexler, 2001). A knowledge map plays important roles in implementing KM. All captured knowledge can be summarized and abstracted through a knowledge. Knowledge maps gather explicit and collected knowledge which can be shared, and facilitate emergence of tacit knowledge of new relationships. Effective knowledge mapping brings map users several returns including economic, structural, organizational culture and knowledge returns (Wexler, 2001). Moreover, knowledge maps can help users locate an effective route, plan, and scenario or sequence of actions, and assist participants in communicating with others regarding the new relationships and ideas using a shared vocabulary. They also help users identify new areas in the emerging search for actionable information.

The key issue in developing a knowledge map is locating important knowledge and then organizing this information. Several approaches exist for knowledge map development.

Knowledge maps have two principal advantages over other knowledge structures: they can be displayed clearly in the KM system, and their mapping methodology helps users to identify the most critical and easily available knowledge areas in the project. Knowledge maps can be represented as file cabinet knowledge maps, cognitive maps, knowledge networking charts, scatter charts, contour charts, list charts, category maps, topic maps, and concept maps (J-B. Yang, 2007).

To develop knowledge maps for the specific sub domain of underground the following steps were carried out: end user analysis; process map analysis; knowledge extraction; knowledge profiling; knowledge linking; and, knowledge map validation.

3.2 *End user analysis*

In large-scale research projects, many researchers from different centers, companies or universities work simultaneously on similar topics. In some cases, different partners carry out complementary research that could be of mutual benefit but do not realizeuntil they see presentations prepared by the other partners.

Other end users include teachers and students, who may require information to create a course, to complete an exercise, or simply to acquire knowledge.

Finally, the community of practice in the field of underground construction will also be another end users. Its potential users are all those interested in underground construction, including researchers, organizations, and individuals, who will be able to incorporate new knowledge and search and retrieve information from previous researchers.

3.3 *Use cases and scenario analysis*

Use cases are objective records of relevant fragments of research activities in a specific field, in this caseunderground construction. They are made up of scenarios, which in turn consist of sequences of steps through which the task objective is achieved. Each of the steps in a scenario is a basic action in the overall use case. Therefore, scenarios can be used to define the foundations and specifications of the knowledge map.

Three use cases have been studied related to the different domains: 1) research project knowledge management; 2) education;and 3) knowledge retrieval from the community of users. Figure 1 shows a summary of the end users and use cases that determine the knowledge map requirements.

3.4 *Research knowledge transfer*

It is well known that knowledge is generally difficult to transfer. There are countless examples of sound research projects never making it to the practice community, and of organizations in need of solutions typically ignoring academic research findings in developing management strategies and practices. There is a large gap between academic research and practitioners and can be found in nearly all disciplines.

Traditionally, knowledge transfer is viewed as information that could be passed on mechanistically from the creator to a translator who would adapt it in order to transmit the information to the user. These classical models implied a hierarchical top-down relationship between the generator of knowledge who holds the resource (knowledge) and the user (receptacle).

To avoid this problem, the latest models to transfer knowledge from the research to practice communities are the communities-of-practice and the knowledge network model. The communities-of-practice are "groups of people informally bound together by shared expertise and passion for a joint enterprise". Because communities of practice generally focus on informal, voluntary gatherings of individuals based on shared interests, they are sometimes seen by organizations as "unmanageable" endeavors. Knowledge networks, on the other hand, which have more organizational support, are believed to contribute directly to the bottom line.

Concretely, in the construction sector, The European Construction Technology Platform (ECTP) is the European community of practice. All European countries have their own national platform. In Spain, the construction platform is called *PlataformaTecnológicaEspañola de Construcción (PTEC)*. These communities of practices include all stakeholders in the construction sector and are industrially driven.

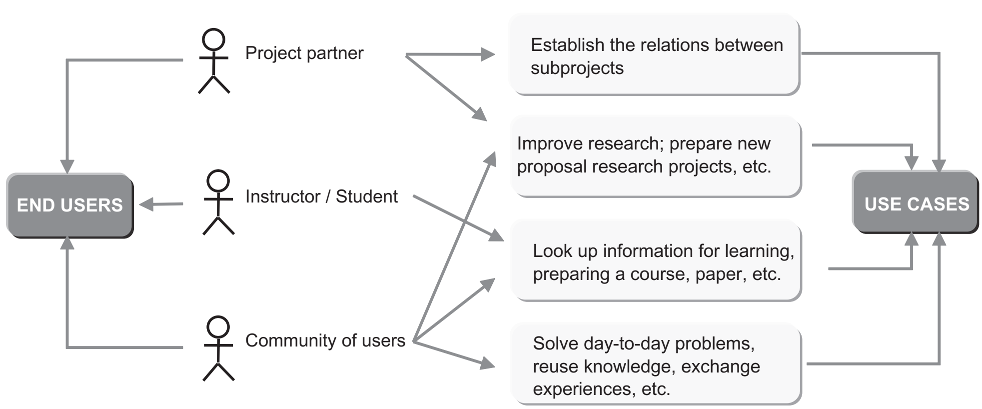

Figure 1. End users and use cases.

4 DEVELOPMENT OF KNOWLEDGE MAPS FOR UNDERGROUND CONSTRUCTION RESEARCH PROJECTS

The use case analysis highlighted a principal set of tasks carried out in underground construction research. The results were used to establish a task-oriented information structure that provides an operational view of all the information used in this type of project and underline the importance of knowledge structuring and multi-perspective indexing and navigation, which are the key information requirements in whatever KM system. Two knowledge maps might represent the underground construction research projects to organize, classify and describe each piece of information, which is called Information Object (IO), and two concept maps are used to represent the knowledge maps:

- The DOMAIN knowledge map shows the basic information of the IO and the processes involved in the construction object.
- The MEDIA knowledge map describes the typology of the IO.

The domain knowledge map is configured as a concept map of underground construction. To do so, different glossaries and thesauri in the field of underground construction were analyzed including the Tunnel Boring Machine Glossary, the 2005 Glossary/Thesaurus produced by the International Tunnelling Association (ITA), the Glossary of Terms for Tunneling Machines (ITA), the Thesaurus—Keywords for Underground Structures (ITA), the *Glossairefrançaisanglais allemande relative aux tunneliers*, 1998, the *Diccionario-GlosarioTécnico de Túneles y ObrasSubterráneas*, and the ISTT Glossary of Terms. Therefore, the domain knowledge map describes the content of each IO using field-specific underground construction terminology.

The domain knowledge map has a very large, multi-level tree structure divided into four category levels. Figure 2 shows the main structure and some of the categories (some are too extensive to be represented here).

The media knowledge map is used to describe the type of IO and is important to the system because researchers often search for specific types of documents, such as regulations or specifications.

From the study of different thesauri and research projects (MACE, 2008, CONNET, 2008) the multi-level structure of the media knowledge map was defined. Figure 3 shows the structure of this map.

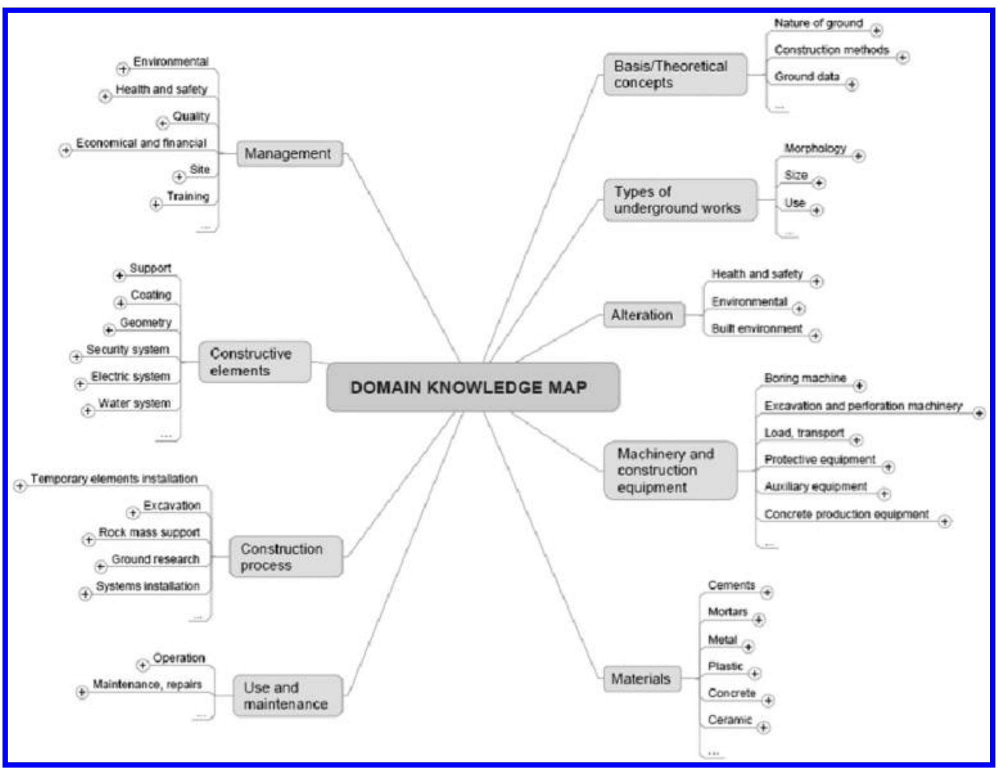

Figure 2. Main structure of the domain knowledge map.

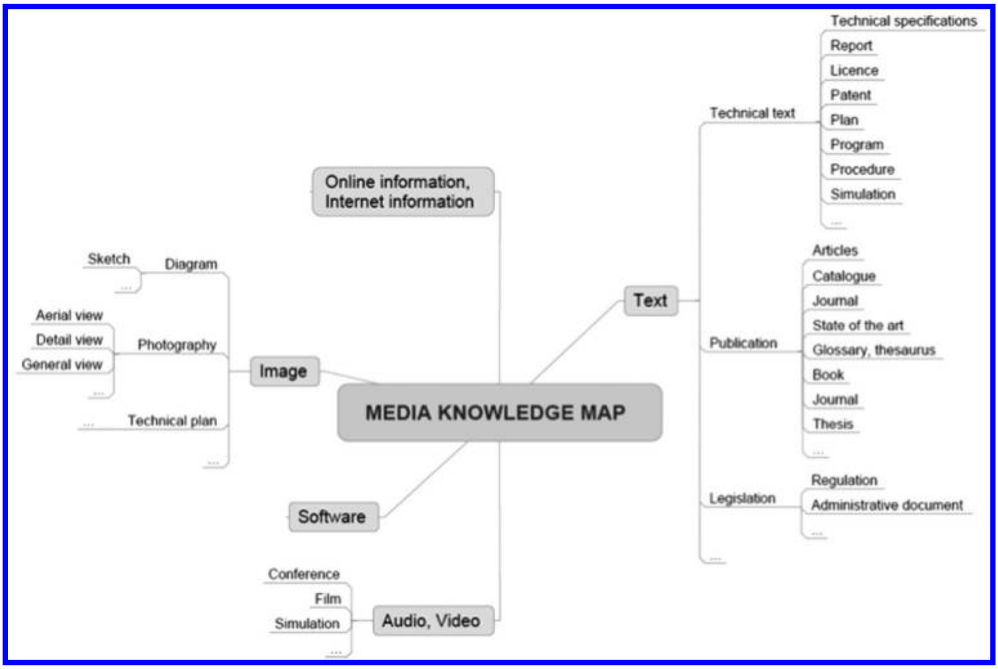

Figure 3. Main structure of the media knowledge map.

5 IMPLEMENTATION OF THE KNOWLEDGE MAPS

To tests both knowledge maps, they were implemented in a knowledge management system to share and disseminate research results of a very big research project in the fiend of underground construction: the Multidimensional City.

5.1 *Multidimensional City project*

The Multidimensional City is a Spanish strategic scientific-technological project from the *Ministerio de Ciencia e Innovación* PSE 10-2005. It is a multi-disciplinary research project that promotes the development and implementation of Spanish technological innovation in underground construction.

The Multidimensional City is a project endorsed by the "PlataformaTecnológicaEspañola de Construcción". The project´s partners integrate not only the on-the-field engineering experience and technical know-how of the industry, but also the research capabilities and conceptual innovation of the academic sector. The Multidimensional City is fully committed to contributing to an increased quality of life by reducing construction time and cost of planned and future underground infrastructures.

The Active Knowledge Management System (SGAC) pretends to be an access web portal to all the knowledge generated inside the The Multidimensional City project: promoting the disseminationof all the results obtained along the different research activities carried out by the project participants, not only along the lifecycle of the project but also once the project is finished; providing tools to make the KM tasks easier along the lifecycle of the project, through the visualization of the reports evolution or the related documents; and providing useful and updated information to academics, researchers and industries in the underground construction field to be used in the preparation of e-learning courses and the learning in general.

On the other hand, the project results not only are interesting from a scientific or technologic point of view, but also from an educational point of view. For this reason an e-learning platform has been developed with the aim of taking profit of all the knowledge generated inside the research project, already introduced and classified in the SGAC system, to be included in e-learning courses for academics, researchers and industries in the underground construction field. The preparation of these e-learning courses will highly contribute to the dissemination of all the research project results.

Currently, the SGAC contains all the knowledge generated along lifecycle of the project.

This knowledge comes from the results obtained along the research tasks developed, as well as all the information used and created along these research tasks. Therefore, reports and deliverables containing the work undertaken by all the project partners, presentations, published papers, images, states of the art, drawings, etc. can be found through the SGAC search tools.

In order to assure efficient searches and to accomplish the users' requirements, all this information has been enriched with different kinds of metadata. When analyzing the knowledge, the metadata to be incorporated in each information object (IO) was defined. With the aim to create an interoperable infrastructure with other possible databases, the system uses as a basis the LOM IEE 1484.12.1 Standard for Learning Object Metadata (IEEE, 2002).

One of the most important metadata are the knowledge maps: domain knowledge map and media knowledge map.

The SGAC system is composed by two different tools, both of them accessible from the SGAC web portal (http://www.lcm-gac.es) with a previous user's validation: the Introduction of contents tool and the Search of contents tool.

The Introduction of contents tool enables the user, with a previous validation, to upload the desired IO to the system and enrich it with the defined metadata fields.

On the other hand, the Search of contents tool provides three different kinds of searches: Simple search, Filtered search and Conceptual search.

The Simple search can search by title and/or description, by keywords from the thesaurus or by whatever field of metadata implemented in the tool.

The Filtered search filters the results by their source (the subproject where the specific IO has been created), the format, the language and the year of creation. On the other hand, this kind of search enables the user to choose a Media keyword and a Content keyword.

And finally, the Conceptual search enables the search of contents through the different categories and subcategories of both Media thesaurus and Content thesaurus. The results of any kind of search are displayed in a list, together with their title, description, source and year of creation.

6 CONCLUSIONS AND FUTURE RESEARCH

Knowledge of construction management has received considerable attention in the construction industry. Research is the most essential issue owing to the fact that it is at the core of construction management. Constructing a well-rounded knowledge map for research in a specific construction sub domain such as underground can make domain knowledge development more matured and provide learners with more comprehensive knowledge. This study generated a main classification of underground construction for research projects. Based on the knowledge map development approach employed in this study, several conclusions can be drawn up:

- The knowledge maps constructed is directly potentially used in web based Systems as it could be noticed in the case study.
- The knowledge map development approach employed in this study was successfully examined for constructing a knowledge map based on a underground construction research projects. This approach will be valuable for similar studies that use searchable databases to construct knowledge maps.
- The developed knowledge maps were validated and implemented in a very big research project but they are not restricted to this knowledge system. They can be implemented in whatever knowledge management system and database.
- Knowledge map construction requires a knowledge engineer familiar with both domain knowledge and knowledge regarding employed technology. Developing a knowledge map in the underground construction research industry requires knowledge engineers with a construction industry background.
- Knowledge management is a non-resisting trend for all industries. The construction industry, frequently regarded as a traditional industry, has few stories regarding successful knowledge management. Promoting construction expertise is essential to acquire knowledge of knowledge management in a scenario of rapid advances in industry innovation.
- Currently, the majority of the research knowledge is shared in face-to-face interactions (project presentations, meetings, etc.) and it is dispersed in different supports (paper based, on line, etc.). With the development of these knowledge maps and their implementation to the SGAC all this knowledge is centralized and accessible for all the project community from a unique web portal. All this information has been analyzed and codified with metadata to assure efficient searches and to accomplish the users' requirements. From the study of all this knowledge the users have realized that some of them are working in similar or complementary research areas. Therefore, the SGAC helps all project partners to know what is being done in other sub projects. On the other hand, the

system is becoming a useful tool to manage all the knowledge generated in the project along its lifecycle.

Future research will be conducted in order to test the suitability of these Knowledge Maps for e-learning. The research will determine whether these Knowledge Maps improves students' learning in an underground construction engineering class. The research also will identify appropriate directions for the use of knowledge management systems in the AEC industry.

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A BIM-based framework for forecasting and visualizing seismic damage, cost and time to repair

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ABSTRACT: A methodology is presented for integrated and automated forecasting of damage assessment, cost estimating, scheduling and of 3D/4D visualizations for post-earthquake building rehabilitation. The proposed methodology is based on the integration of Building Information Modelling (BIM) and Assembly-Based Vulnerability (ABV) techniques. ABV is a framework for evaluating the seismic vulnerability and performance of structures on a building-specific basis, utilizing seismic analysis techniques to determine the structural response of a building. The methodology used accounts for structural and non-structural building components and corresponding fragility curves, and subsequently applies BIM-based techniques to automate the generation of cost estimates, activity schedules as well as 3D/4D visualizations of the associated rehabilitation work.

1 INTRODUCTION

1.1 *Motivation*

The Architecture, Engineering and Construction (AEC) industry has long strived for improvements in the manner it develops and implements projects and, despite the strong inertia it has shown to adopting new technologies, it has embraced three-dimensional visualization in its quest to improve current practices within the industry. The premise has always been that the transition to BIM would offer considerable benefits in all stages of the AEC process.

A similar revolution in structural engineering has seen the rise of Performance-Based Earthquake Engineering (PBEE), where the profession is slowly moving away from the classic design of a code-conforming building (i.e. the one-design-fits-all model) to the production of improved designs tailor-made to fit the performance requirements of a particular building owner. Thus the owner can now decide upon the level of performance (i.e. safety) that is desired for a certain building at each possible level of earthquake shaking that it may experience. Still, the communication between the owner and the engineer has always been troublesome, as the engineering descriptors of performance (e.g. inter-storey drift, plastic rotation or shear capacity) are typically meaningless outside the civil engineering profession. Recent attempts to quantify performance in more tangible terms, such as rehabilitation cost, casualties or time to repair (Miranda and Aslani 2003, Gouler et al. 2007) have greatly improved the situation but they still fail to provide a comprehensive understanding of the building's behavior to the average non-engineer. Therefore, it is only natural to couple PBEE with 3D/4D visualization techniques to facilitate the communication between the owner and engineer.

1.2 *Literature review*

The benefits of BIM have been extensively researched and documented (Collier and Fischer 1996, Fischer 2000, Griffis and Sturts 2000, Christodoulou 2001, Akinci et al. 2002, Koo and Fischer 2000, Kamat and Martinez 2001). The technology and its several incarnations have proven to be a particularly useful communication, planning, and analysis tool for designers, engineers and constructors. At the core of these technologies lies the need to improve on the visual representation of the facility under design or construction. To that extent, the desired high level of visualization of architectural and engineering designs has been the primary driving force for developments in three-dimensional visualization in the AEC industry.

PBEE is the natural evolution of the structural design process to encompass the growing need for specialized structures tailored to the needs of each individual owner. It allows the design of structures that can withstand frequent or rarer earthquakes with the desired performance, for example remaining fully operational for low intensity frequent earthquakes, sustaining low damage at less frequent events and perhaps needing heavy repairs or replacement but maintaining structural integrity at the rarer and most intense levels of shaking. Several guidelines that recognize such needs have appeared in recent years, e.g. SAC/FEMA-350/351, FEMA-356 and ATC-40 (SAC 2000a, SAC 2000b, FEMA 2000, ATC 1996).

A prominent example is the PEER Center methodology (Cornell and Krawinkler 2000) that has been developed to offer a comprehensive assessment of the building performance at any level of shaking and any desired limit-state by integrating the seismic hazard and the structural analysis results with damage and cost estimation to produce realistic estimates of the cost associated with any earthquake.

What has been missing is a way to visualize such results on an actual 3D structure using existing professional software as the means to facilitate the communication between client and engineer. Building owners rarely understand the technical language used by engineers and often fail to realize the differences between the design alternatives offered and their actual seismic performance. Improved performance typically means investing a higher initial construction cost that is expected to be more than paid off by the decreased damages experienced in the design life of the building.

Thus, proper communication of the implications of any design decision is essential, in order to facilitate the commitment of the necessary funds.

Unfortunately, current practice limits the information exchanged between owners and engineers to a handful of numbers, which are usually meaningless to the clients. Even when attempts are made to approximately estimate the actual repair cost and downtime in an earthquake scenario, such numbers carry a high uncertainty that is often in the order of 100% or more.

Furthermore, single numbers often fail to communicate an important feature that is a primary target of PBEE, namely the actual level of operability of the structure after any minor or major event. PBEE has been all about integrating structural damage (beams, columns) with non-structural (HVAC, doors, partitions) and building contents' damage. Without the proper visualization capability such numbers become mute. For example, any significant debris on a hospital corridor could easily render a number of rooms useless or inaccessible. Such implications are impossible to decipher from the output of any existing structural analysis program, let alone explaining them to the client.

Having PBEE analysis results available on the 3D level simplifies understanding considerably. Clients are now able to identify restricted areas, plan for possible routes for moving material and personnel and in general gain a proper understanding of the post-earthquake capacity of the structure to function as intended. To achieve this goal we propose to couple current PBEE practice together with readily available visualization techniques that can be implemented in any professional design office.

2 INTEGRATED DAMAGE ASSESSMENT AND 3D VISUALIZATION

2.1 *Real-time condition assessment of constructed facilities*

Typical real-time monitoring systems consist of tens of wireless nodes placed at various locations in the structure being monitored collecting and transmiting sensor data to a remote base-station. A multi-parameter visualization and decision-support system is then responsible for detecting and localizing any abnormalities in the structure and for producing early notifications and suggestions, which are then distributed to field engineers and maintenance technicians for their actions.

In the case, though, of constructed facilities (such as buildings) or hard-to-reach infrastructure (such as underground piping networks) the deployment of sensors is both costly and difficult (if not impossible sometimes). In such cases, post-construction sensor placement and data transmission capabilities are achieved by ad-hoc wireless networks (WSN).

2.2 *Computational performance assessment*

Sensors are useful when engineers are in need of seeing what really happened or maybe getting a sense, in real-time, of what is going on in a building after a quake without having to physically go and inspect the building (Naeim et al. 2006). On the other hand, using PBEE and in turn Incremental Dynamic Analysis (IDA) (Vamvatsikos and Cornell 2002) and Assembly-Based Vulnerability (ABV) (Porter et al. 2001) methodologies (that fit into the PBEE paradigm) engineers take a predictive approach, where they try to figure out what may happen in certain earthquake scenarios. ABV is a framework for evaluating the seismic vulnerability and performance of structures on a building-specific basis (Porter et al. 2001). The method utilizes seismic analysis techniques to determine the structural response of a building (e.g. IDA), accounts for structural and non-structural building components and corresponding fragility curves, and subsequently applies FIAPP-based techniques to automate the generation of cost estimates, activity schedules as well as 3D/4D visualizations of the associated rehabilitation work.

The ABV method (Porter et al. 2001) and similar methods by Miranda and Aslani (2003) make use of the simulated behavior of each assembly in a building and a corresponding fragility function to determine the probability that the assembly will be damaged and require repair or replacement. The probability is then used to simulate the damage state of each assembly in the building and to approximate the unit cost and duration to repair each such assembly.

Assemblies are based on either custom-defined work breakdown structures (WBS) or on industry-wide taxonomies such as the Construction Specifications Institute's (CII) Masterformat. The damage state of a particular assembly is considered to depend on the structural response to the load which it is subjected to, and the corresponding total cost for bringing the assembly back online is a combination of the repair cost and the loss-of-use cost. A definition of these costs as well as the time to repair each operational unit can be found in Porter et al. (2001).

3 INTEGRATED COST-ESTIMATING AND SCHEDULING FOR POST-EARTHQUAKE BUILDING REHABILITATION

The PEER methodology together with the ABV method is merged with BIM to generate a fully integrated and automated platform for visualizing all post-earthquake building rehabilitation functions (damage assessment, cost appraisal, work schedules, 3D visualizations, 4D sequencing). The process is depicted in Fig. 1.

At first, a 3D object-based model of a building is constructed in conformance with the BIM and IFC paradigms. The model, which was developed in Graphisoft's ArchiCAD software, contains both structural (beams, columns, slabs, etc.) and non-structural (walls, ductwork, furnishings, etc.) building components and it is used both as a visualization tool and as an information repository. The model (a case-study three-storey concrete building) is used to generate several item listings for quantity-takeoff and cost-estimating purposes, or for structural-analysis purposes.

A relational database management system (RDBMS) is developed concurrently with the 3D model containing the project's WBS and underlying building assemblies, CSI codes, unit cost and production rates. The RDBMS provides links between the BIM objects and the rest of the database tables archived in it, through the primary keys of each data-base table. For example, each BIM CAD object has a unique ID which is linked, through a mapping table, to a CSI code and through that to a crew code. The mappings can be of type "one-to-many" or "many-to-one", allowing the user to assign several BIM objects to one or several CSI codes as needed. For example, a "concrete column"

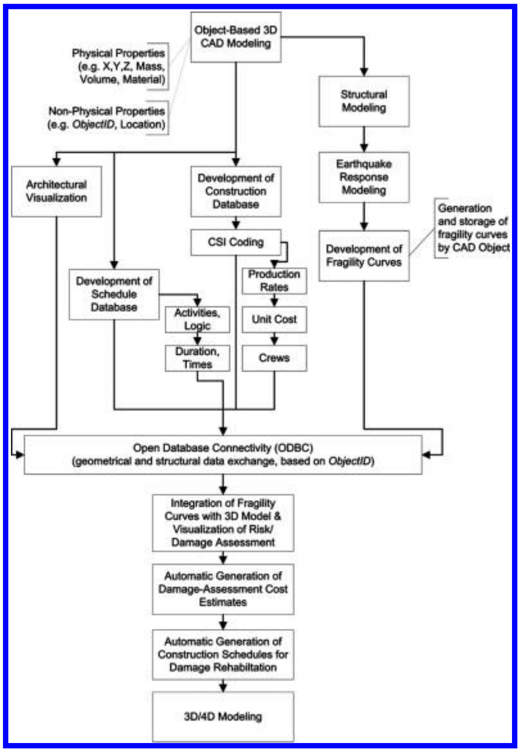

Figure 1. Flowchart of proposed post-earthquake damage assessment and visualization.

object can be assigned to "formwork", "casting", "insulation" and "painting" CSI codes.

The physical properties of an object (mass, surface, length, volume) in conjunction with the production rates from the CSI codes assigned to it dictate the duration of the corresponding damage-rehabilitation activity. It should be noted that, since the goal is the creation of damage-assessment cost and time estimates which are as complete as possible, the 3D model also contains building contents (Fig. 2).

The RDBMS also contains construction-sequencing templates ("fragnets") addressing possible rehabilitation scenarios. The schedule fragnets include the relationships between the construction activities and typically follow the WBS/CSI structure (activities with lower CSI masterformat codes pre-cede activities with higher CSI codes). The duration of each activity in a fragnet is computed based on the BIM objects included in the activity and the production rate of the crew assigned to them is based on the CSI code for each object (Fig. 3).

The 3D model and BIM information (object attributes) are used in the structural analysis of the building and in the investigation of the response to

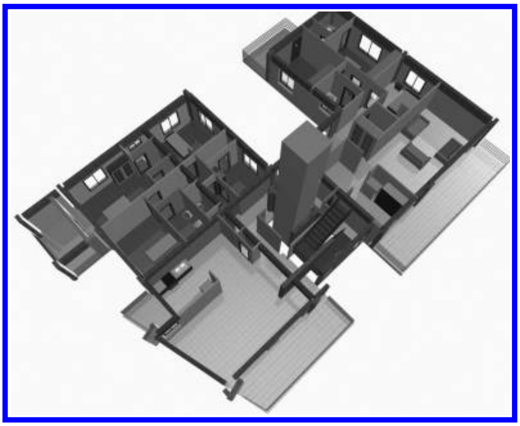

Figure 2. 3D BIM of case-study building floor with structural, non-structural components contents in undamaged state.

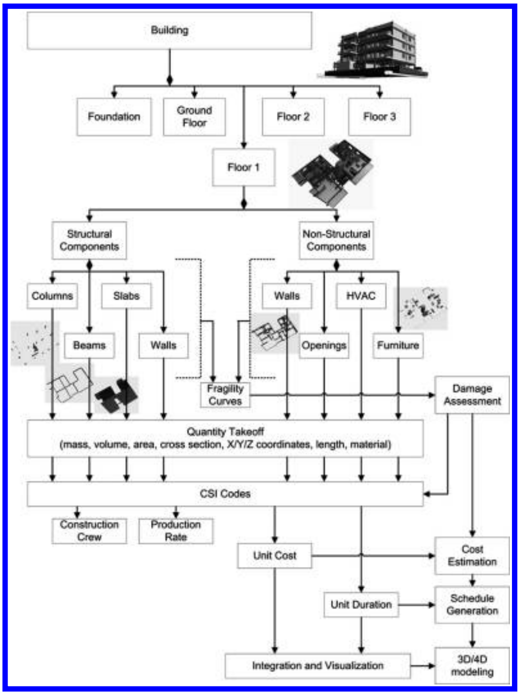

Figure 3. Schematic of BIM/ABV/Cost/Schedule/4D integration.

earthquake loads, by utilizing predefined assembly-based libraries and fragility curves. Once a structural assessment is made, a "damage measure" per building component is computed subject to the fragility curves associated with each component. Fragility curves relate structural response with various levels of damage, producing the probability of a structure (or structural component) reaching or exceeding a particular damage level. The gradients of damage vary, but typically they are classified as "zero, or slight", "moderate", "severe" and "total" damage.

Therefore, the damage measure and damage state produced by the structural analysis and the fragility curves for each building assembly can be jointly used as general "damage descriptors" that can in turn be visualized by use of appropriately coloring a 3D BIM model. In the case-study 3D BIM, the variables visualized are: (i) the damage state, (ii) the repair cost, and (iii) the repair time. The damage measure can be either a continuous variable in the range [0, 1] (with "0" indicating no damage and "1" indicating collapse), or a discrete variable, appropriately colored: (i) Green - slight or no damage, no action needed, (ii) Yellow - moderate damage, repairable, (iii) Red - severe damage, needs replacement (repairs are not cost-effective), and (iv) Black - total loss. Cost and time are represented as continuous variables and can be colored as in a typical contour plot. Progressive damage/collapse is currently not taken into account.

The cross-referencing of fragility curves with BIM objects and CSI codes generates the recommended action ("rehabilitate or replace" dilemma), the cost-to-rehabilitate and the associated duration (snapshots shown in Tables 1 and 2. Furthermore, the damage-assessment information is related back to the 3D model by means of an ODBC conduit that passes to the BIM the damage state of each assembly object as an attribute of it. This enables the 3D-visualization of the building damage state by selectively coloring 3D objects based on their damage level (Fig. 4).

The case depicted herein corresponds to a post-earthquake scenario involving slight damages in the top floor of the building and some moderate damages in the first floor. The scenario further asserts "strong column, weak beam" behavior which confines the structural damage to the beams only. The collateral damage includes the windows of the first and fourth floor (all flagged as "severe damage"), the interior and exterior walls above which the beams suffered moderate to severe damage, and the floor contents in proximity of walls that suffered moderate or severe damage.

4 CONCLUSIONS

The paper presents an integrated approach to assessing and visualizing post-earthquake building damages, by means of integrating a building information model with relational databases, 3D/4D computer-aided models and assembly-based vulnerability paradigms. The resulting

Table 1. Damage assessment of building assemblies (excerpt) based on fragility curves.

WBS/assembly component				Fragility/structural analysis					
Floor	Room	Object type	Object ID	Damage measure	Damage state	Action	Fragnet ref. code	Total cost ($)	Total dur (d)
1	101	Beam	BMR-001	0.22	Moderate	Rehab	BMR-RHB	10,000	10
1	101	Beam	BMR-002	0.32	Moderate	Rehab	BMR-RHB	10,000	10
1	101	Beam	BMR-003	0.25	Moderate	Rehab	BMR-RHB	10,000	10
1	101	Beam	BMR-004	0.28	Moderate	Rehab	BMR-RHB	10,000	10
1	101	Column	CLM-001	0.04	Slight	None	–	0	0
1	101	Column	CLM-002	0.05	Slight	None	–	0	0
1	101	Column	CLM-003	0.08	Slight	None	–	0	0
1	101	Column	CLM-004	0.02	Slight	None	–	0	0
1	101	Ext. Wall	EWL-001	0.15	Moderate	Rehab	EWL-RHB	2,000	4
1	101	Ext. Wall	EWL-002	0.17	Moderate	Rehab	EWL-RHB	2,000	4
1	101	Int. Wall	PRT-001	0.05	Slight	Rehab	PRT-RHB	1,000	1
1	101	Int. Wall	PRT-002	0.03	Slight	Rehab	PRT-RHB	1,000	1
1	101	Window	WND-001	0.60	Severe	Replace	WND-RPL	1,500	1
1	101	Window	WND-002	0.45	Severe	Replace	WND-RPL	1,500	1
1	101	Window	WND-003	0.62	Severe	Replace	WND-RPL	1,500	1
1	101	Door	DOR-001	0.65	Severe	Replace	DOR-RPL	1,000	1
1	101	Wardrobe	FRN-001	0.16	Moderate	Replace	FRN-RPL	350	0.5
1	101	Bed	FRN-002	0.21	Moderate	Replace	FRN-RPL	250	0.5
1	101	Desk	FRN-003	0.15	Moderate	Replace	FRN-RPL	150	0.5

Table 2. Cost and duration (excerpt) for post-earthquake damage rehabilitation.

Fragnet ref. code	Activity ID	Description	CSI code	Quantity to use	Unit cost ($)	Unit duration (d)
BMR-RHB	1	Remove debris	017419	Volume	50.00	0.5
BMR-RHB	2	Reinforce	032000	Volume	150.00	1.0
BMR-RHB	3	Formwork	031113	Area	120.00	1.0
BMR-RHB	4	Concrete pour	033000	Volume	150.00	0.5
BMR-RHB	5	Concrete curing	033900	Each	10.00	0.5
BMR-RHB	6	Interior painting	099123	Area	50.00	7.0
WND-RPL	1	Remove window frame	017419	Area	50.00	0.5
WND-RPL	2	Rehab. wall opening	064800	Area	75.00	0.5
WND-RPL	3	Concrete pour and curing	033900	Volume	150.00	0.5
WND-RPL	4	Install new window frame	064613	Area	75.00	0.5
WND-RPL	5	Exterior painting	099913	Area	50.00	0.5

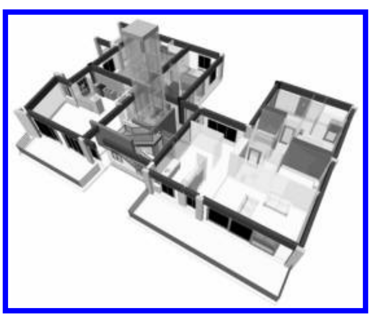

Figure 4. BIM/ABV integration—3D rendering of building floor showing floor's damage state (darker colors indicate greater damage).

approach is a valuable tool for AEC industry participants, for it allows the automation of structural, cost and scheduling analyses and their integration with 3D/4D visualizations of buildings for the purpose of holistic damage assessments in the aftermath of an earthquake. The methodology can also be considered a "first-responder" approach to mediating the effects of earthquake-induced building damages, since it allows for hierarchical analyses of the damages of building components and subsequently the cost and time estimation for the rehabilitation of such damages, in a visual manner that is easily comprehensible by the stakeholders of each structure under investigation.

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Web based computing environment for prediction of approximate seismic response parameters of structures

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ABSTRACT: Newly emerging social and technological trends are changing business processes as we know, affecting the way professionals in the AEC industry work. There is an emergent need for a novel distributed software platforms capable of addressing the real-world needs of the scientific and engineering AEC community by allowing them to exploit distributed resources and solve complex problems through controlled, secure, intuitive and technology-hiding means leveraging both the current networking and advanced computing environments. To present the benefits of the above-mentioned computing environment services, a web application for prediction of approximate IDA curves of reinforced concrete structures that enables quadrilateral idealization of the pushover curve including the strength degradation has been recently developed.

The paper provides an overview of the ICE4RISK project as well as a brief description and discussion of the underlying technologies used in the development of the computing environment.

1 INTRODUCTION

Incremental Dynamic Analysis (IDA) is a well-known parametric analysis method, which involves subjecting a structural model to one (or more) ground motion record(s) and to multiple levels of seismic intensity (Vamvatsikos & Cornell 2002). IDA provides seismic response parameters for the entire range of intensities all the way to the global dynamic instability of the structure. However, it requires a large number of inelastic time-history analyses and detailed data on ground motion time-histories and hysteretic behavior of structural elements. As such it is very time-consuming. Therefore, different procedures have been recently proposed, which enable prediction of approximate IDA curves with less input data, with less effort, but with still acceptable accuracy.

The simplified inelastic procedures used in seismic design and assessment combine the nonlinear static (pushover) analysis and the response spectrum approach or nonlinear dynamic analysis of a Single-Degree Of Freedom model (SDOF). One of such procedures is the N2 method which has been developed at the University of Ljubljana and implemented into the Eurocode 8 standard. The inelastic spectrum, which is prescribed by Eurocode 8 and used for the determination of the target displacement, allows only a rough bi-linear idealization of the pushover curve and assumes an unlimited ductility.

In this study an attempt has been made to predict the target displacement by four-linear idealization of the pushover curve by using the approximate SDOF-IDA curves. Instead of calculating the SDOF-IDA curve for particular input parameters that describe the equivalent SDOF system, a large database of SDOF-IDA curves which correspond to uniformly distributed input parameters (i.e. periods, damping ratios, force-displacement envelopes) and different ground-motion records, has been established. Combining the database of the SDOF-IDA curves with a simple approach can predict the IDA curve for a specific structure known as the n-dimensional linear interpolation. The application of the proposed methodology has been demonstrated with the help of a four-storey reinforced concrete structure. The results obtained by the simplified nonlinear seismic assessment method have been compared with the results based on the IDA analysis.

The advantage of the applied methodology for the prediction of the approximate IDA curves is the fact that the parametric study can be the subject of a large number of parameters that affect the seismic response. In addition, the response database and the procedure for determination of the approximate IDA curves based on the results stored in the database are independent. Therefore the response database can be easily upgraded with the new data, for example by adding the response for different set of ground motion records, which is automatically considered in the prediction of the approximate IDA curves.

The objective of this paper is to present the web application for the prediction of the approximate

IDA curves of reinforced concrete structures, which has been recently developed under the ICE4RISK project. Instead of developing a new closed platform solution, the ICE4RISK project introduces an innovative computing environment by leveraging different existing and emerging technologies, including: Web 2.0, cloud computing, grid technology and Software-as-a-Service (SaaS). The main focus has been put on the developed web-based system, its characteristics derived from the emerging technologies and its benefits compared to traditional seismic engineering work practice.

2 SUMMARY OF THE METHODOLOGY FOR THE PREDICTION OF THE APPROXIMATE IDA CURVES

The methodology that has been recently proposed for the determination of approximate IDA curves consists of two independent processes (see Figure 1).

The first process is the parametric study performed for the SDOF system. It involves a definition of the input parameters that affect the seismic response, definition of the discrete values of the input parameters, and computation of the IDA curves of the defined SDOF systems. Since the inelastic seismic response is performed only for the SDOF system, the usual input parameters are the period of the system, the parameters of force-displacement relationship and hysteretic behavior, the damping, and the ground motions. However, the selection of the force-displacement relationship or hysteretic behavior of the SDOF system that would be appropriate for simulating the global response of a specific structural type is not trivial. It is worth to emphasize that the parametric study depends on the expert judgment. Different experts may select different input parameters or their discrete set of values. Therefore it is important that the process of the parametric study is independent of the second process since many different databases may be created in the future.

The second process involves the prediction of the approximate IDA curves based on the established response database. Also this process can be further sub-divided. In general there are two steps; the query for the appropriate IDA curves from the database and the computation of the approximate IDA curves by the selected interpolation method. Among various interpolation methods such as linear interpolation, polynomial interpolation, spline interpolation, interpolation via Gaussian processes etc., which are commonly used to model sparsely sampled data, the linear interpolation is the simplest and therefore used in this study. The n-dimensional linear (also known as multi-linear) interpolation is defined by applying one-dimensional linear interpolation in each separate coordinate dimension (Mathpages 2008).

The second step of the proposed methodology involves the prediction of the approximate IDA curves from the database. In general, this process, too, can be sub-divided into four processes (Figure 1). While the first step, i.e. the selection of the input parameters corresponding to the particular case study, is rather trivial, the complexity of the second and third step depends mostly on the selected method that is used for interpolation.

There are several reasons to implement the presented methodology through the web application. Firstly, the database of the IDA curves can contain considerable amount of data and as such is not appropriate for distribution. Although anyone can create his own database, it is unlikely that many researches or users will do so since the determination of the database is computational and time

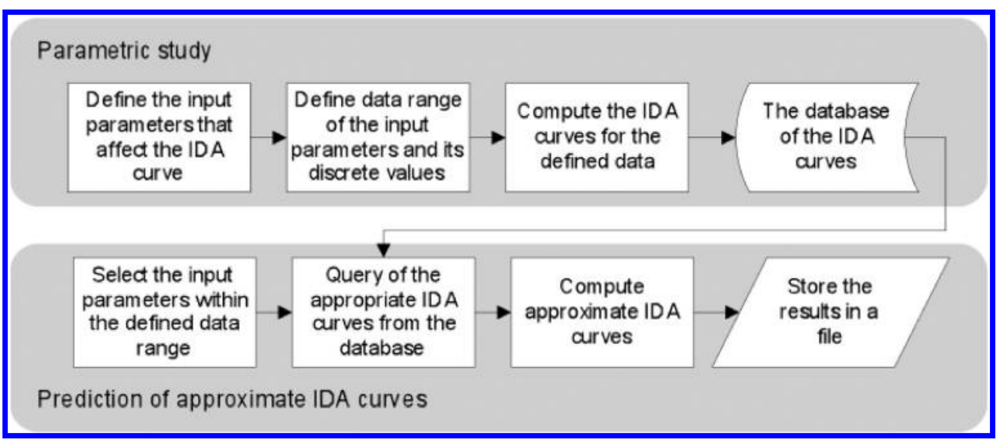

Figure 1. The methodology for determination of the approximate IDA curves.

demanding and also requires specific knowledge, which is usually not in the domain of the potential users. Therefore it is most appropriate that the database is stored and maintained in one place and can be easily accessible through the Internet.

The most convenient access to the database is through the web application that is simply accessible and user-friendly.

Due to the above-mentioned reasons we suggest the Software as a Service (SaaS) model of software deployment, which allows us to develop, host, operate, maintain and upgrade software from a central location (web server) for global use.

The advantages of such environment are operating system independence, no need for installation and no maintenance cost. In addition, web based application can be accessed from anywhere at any time, which makes it even more attractive.

3 DRIVING TECHNOLOGIES

The following sections describe various new and emerging information technologies that were used in the course of the development of the ICE4RISK project computing environment that addresses different development issues of the required computing infrastructure.

3.1 *Web 2.0*

In the recent years, the phenomenon of Web 2.0 attracted a lot of attention not only on the Internet, but also in the business community. New on-line applications not only make tasks such as individual and group on-line learning, communication, collaboration and creation easier, they also have the capability of upgrading the experience by using the vast amount of information from the Internet, previous sessions and so-called collective intelligence of its users. It is considered as a next step and a major evolution of the traditional web from both the technological and social perspective.

It is not possible to define the classic and next generation web by describing the technology. Instead, the focus has to be put on the changes in human behavior that the technology enables, whereas those changes are difficult to describe or define. Therefore it is not surprising that it is difficult to define Web 2.0 since there is no clear definition of Web 1.0 either. Both principles are more or less always presented as a comparison between them.

Tim O'Reilly (2006) proposed the Web 2.0 compact definition was formed as follows: "*Web 2.0 is the business revolution in the computer industry caused by the move to the internet as platform, and an attempt to understand the rules for success on that new platform. Chief among those rules is this: Build applications that harness network effects to get better the more people use them.*"

3.2 *Cloud computing*

Hewitt (2008) as well as Happell (2008) have recently defined cloud computing as a paradigm in which information is permanently stored on servers on the Internet and cached temporarily on clients that include desktops, entertainment centers, tablet computers, notebooks, wall computers, handhelds, sensors, monitors, etc.

The cloud is a metaphor for the Internet, which is based on the way it is depicted in computer network diagrams. Besides, it is an abstraction for the complex infrastructure it conceals. It is a style of computing in which IT-related capabilities are provided as a service allowing users to access the technology-enabled services from the Internet without the knowledge of, expertise with, or control over the technology infrastructure that supports them. Cloud computing is a general concept that incorporates Software as a Service (SaaS), Web 2.0 and other technology trends in which the common theme is reliance on the Internet for satisfying the computing needs of the users. The cloud-based services can be grouped into three broad categories:

1. Software as a Service (SaaS) application runs entirely in the cloud and typically with an internet browser as a client;
2. Attached services that present a combination of offline and online application components; and
3. Cloud platforms provide the cloud-based services for application development and deployment.

Cloud computing is often confused with grid computing, utility computing (Sharma 2008) and autonomic computing (Miller 2008). Many cloud computing deployments are currently powered by grid infrastructures, have autonomic characteristics and are built as utilities; but cloud computing can be seen as a natural next step. Some successful cloud architectures have little or no centralized infrastructure or billing systems whatsoever, including peer-to-peer networks and volunteer computing (Dolenc & Dolšek 2008).

More on driving technologies in AEC can be found in Klinc et al. (2009).

4 IMPLEMENTATION

The web application was built following the classic three-tier client-server architecture, which enforces a general separation of three parts: the client tier (also named the presentation layer or, more specifically, user interface), middle tier (business logic) and data storage tier (Figure 2).

4.1 *Presentation layer*

The top-most level of the application is the user interface on the presentation tier of the system. Its main function is to translate tasks and results to something the user can understand. In our application the presentation is disseminated through a web browser which handles web pages encoded in (X)HTML language and generated by a web server on the layer of business logic.

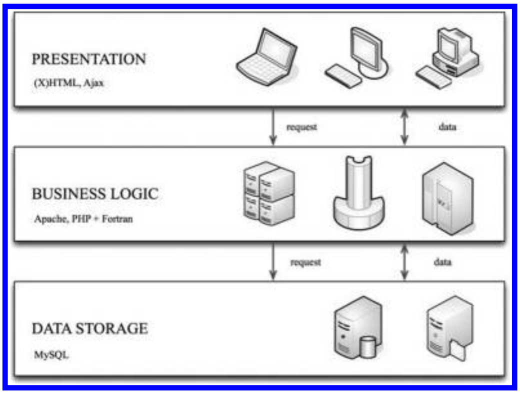

Figure 2. Three-tier architecture of the web application.

Calls between the user interface and the web server are both synchronous and asynchronous. For asynchronous calls, Ajax web programming approach was applied.

4.2 *Business logic layer*

The business logic layer is based on the Apache web server running on the Linux platform. Requests are handled by scripts written by using the PHP programming language which are processing input parameters, interacting with relational database, parsing results and preparing output (X)HTML pages. For mathematically advanced processing, Fortran script is used. Details of the activities on the layer of business logic are presented in Figure 3.

4.3 *Data storage layer*

Data is stored in a relational database. On the basis of the excellent connectivity with the PHP programming language and the Apache web server it was decided to use the MySQL relational database. Another reason is the fact that it is open source software, available without charge. In the test environment, the whole system resides on one server; however, the architecture is scalable so the business logic and data layer can be distributed to different physical servers if the requirements emerge.

In the first iteration, the database of analysis results had approximately 5 million records spread over 2 relational tables and occupied almost 400 MB

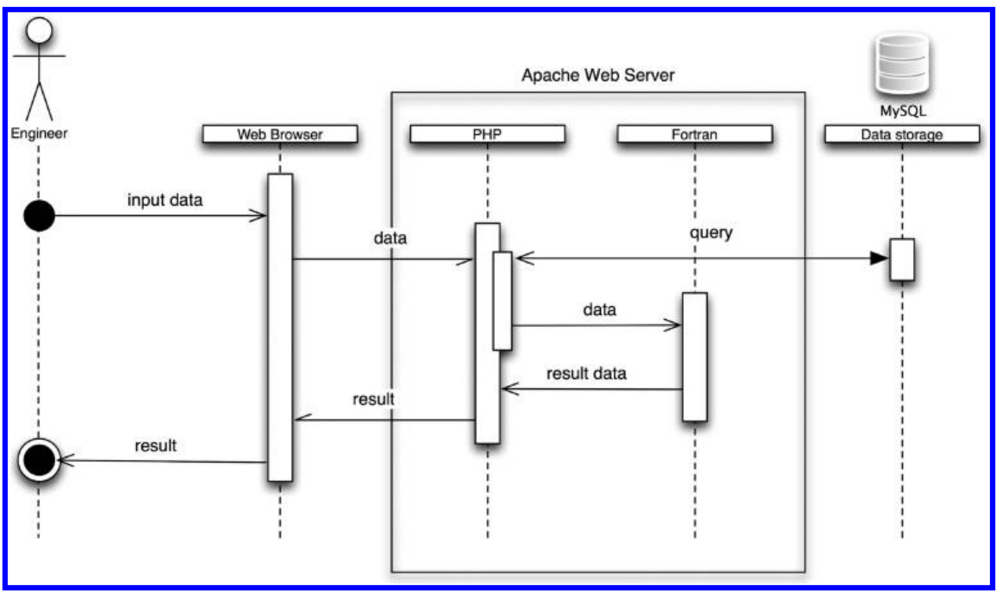

Figure 3. Web application sequence diagram.

of space. However, after the normalization and optimisation the database now has approximately 450,000 records in two relational tables and occupies roughly 170 MB of space. As a consequence, the calculation and response time dropped drastically from the initial 30 s to less than a second (for combined input and output processing).

5 WEB APPLICATION OF THE CASE STUDY

In order to demonstrate the methodology for the prediction of the approximate IDA curves by using the web application, a four-storey reinforced concrete structure was selected and tested.

The structural model was developed in compliance with the Eurocode 8 (CEN 2004) requirements. Beam and column flexural behavior was modeled by one-component lumped plasticity elements, composed of an elastic beam and two inelastic rotational hinges (defined by the moment-rotation relationship). The element formulation was based on the assumption of an inflexion point at the midpoint of the element. For beams, the plastic hinge was used for major axis bending only. Bilinear moment-rotation relationships were used for the first part of the moment-rotation relationship. In the second part of the moment-rotation relationship the linear strength degradation was assumed. The axial forces due to gravity loads were taken into account when determining the moment-rotation relationship for plastic hinges in the columns. All analyses were performed by OpenSees (McKenna & Fenves 2007) in combination with PBEE toolbox (Dolšek 2009). The details of the analysis can be found in Klinc et al. (2010).

Once all the necessary parameters were determined, the web application was used and the approximate IDA curves were determined. The user interface of the web application and the resulting approximate IDA curves are presented in Figure 4 and Figure 5, respectively.

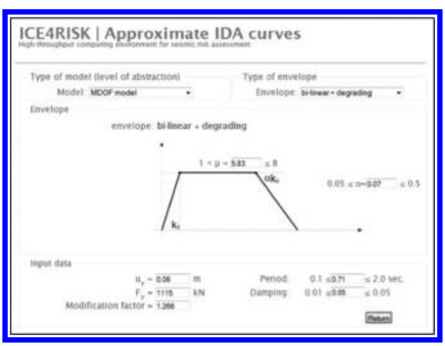

Figure 4. The user interface of the web application.

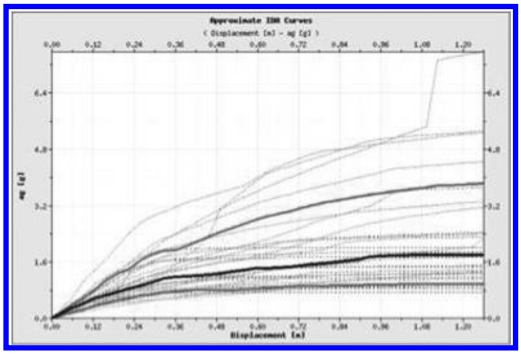

Figure 5. The approximate IDA curves determined by the web application.

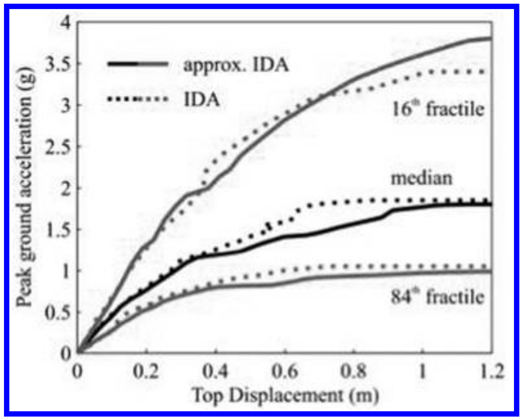

Figure 6. The comparison of the fractile IDA and the approximate IDA curves.

In addition to graphical results, the results are stored also in the file and can be used for further processing.

With the aim of a comparison, the IDA analysis (Vamvatsikos & Cornell 2002) was performed. Therefore Figure 6 shows the comparison of the 16th, 50th and the 84th fractile IDA curve with the approximate IDA curves. A very good agreement can be noted.

6 CONCLUSIONS

A web application for the prediction of approximate IDA curves has been developed. It enables fast and accurate prediction of the approximate IDA curves of the reinforced concrete structures by using quadrilateral idealization of the pushover curve.

The main advantage of the developed tool compared to the traditional approaches used for the determination of the approximate seismic response of structures is the fact that it can be easily upgraded and accessed from anywhere at any time, which makes it even more attractive. Therefore the proposed approach has the ability to significantly improve the simplified nonlinear procedures for seismic performance or risk assessment of structures in the future.

There are several open issues concerning the utilization of high-end computing environments, including scalability, usability and economic issues. The ICE4RISK computing environment addresses these issues by adopting Web 2.0 technologies and cloud computing. Although SaaS deployment model has been selected for the first implementation of the ICE4RISK computing environment, the attached services and cloud platform are also being actively investigated as possible service deployment alternatives.

ACKNOWLEDGEMENT

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Generation of 2-D displacement fields from experimental data using interactive image processing

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ABSTRACT: This work arises from a need to classify the material properties of the tracheal cartilage of leatherback turtles. Using frames from an experimental recording the user may define the boundary geometry of the specimen using spline representations. An interactive program was developed that allowed individual video frames to be processed. The boundary representations from each frame are then combined to give a 3-D time-displacement digital model of the experimental responses.

The 2-D experimental displacement field from a specific experiment is presented. It is shown that the image processing software allows easy digitisation of the experimental displacement fields. The corresponding 3-D time-displacement digital model is also presented.

1 INTRODUCTION

Cartilage is located in areas where mild resistance to compression, tension and shear (in differing arrangements depending on the situation) must be combined with rigidity and some adaptability. The matrix in which the cartilage cells (chondrocytes) are implanted differs both in appearance and nature. There are three types of cartilage; hyaline, elastic and fibrocartilage. Tracheal cartilage is a form of hyaline cartilage. Developed hyaline cartilage is distinguished from the other two varieties by its semi-transparent colour. It consists of small clusters of chondrocytes embedded in an unstructured matrix of ground substance that is strengthened by collagen fibers which are designated as collagen type II. The perichondrium, in the adjacent layer is composed of collagen fibers and spindle-shaped cells which resemble fibroblasts. Previous studies have shown that collagen is a nonlinear material (Sun et al., 2004). It follows that tracheal cartilage is also nonlinear and this has been confirmed in recent studies (Teng et al., 2007; Teng et al., 2008; Teng et al., 2009).

The principal geometrical structure of trachea in vertebrates is composed of stiff hyaline cartilage rings interlocked axially with a flexible tissue membrane. The ensuing pipe-like structure has ample stiffness radially to remain open for respiration and yet, has a low torsional stiffness to allow relatively large neck movements. The cartilage rings may be incomplete (c rings) as is the case in most mammals. However, in some diving animals, such as the leatherback turtle (*Dermochelys coriacea*), the trachea consists of near complete elliptical rings of hyaline cartilage.

The motivation for this work is the long term goal of simulating the response of the entire trachea of leatherback turtles during deep dives (Davenport et al., 2009; Houghton et al., 2008). In order to do this, knowledge of the constituent material parameters of the tracheal cartilage of the leatherback turtle is a necessity. As tracheal cartilage is a nonlinear material and its geometry is irregular it is difficult to compute these parameters using conventional methods. To determine these parameters an inverse methodology is being utilised. By comparing experimentally measured responses of the trachea with those predicted by Finite Element (FE) theory, it is assumed that the material parameters may be determined using an unconstrained optimisation approach. In developing the FE model it has been determined in a previous study (Murphy et al., 2010) that the geometry of the model plays an important role in acquiring accurate results. As a means of obtaining accurate geometric representations of the specimen as it is being deformed in the experiment an image processing methodology was developed. This approach aims to provide the FE model with digitised 2-D displacement fields which may subsequently be used to predict the theoretical deformation of the specimen, in line with the experimental data. As the specimen is near elliptical in appearance it is hypothesised that by fitting a closed cubic B-spline to the boundary on the image, an accurate geometrical representation will be obtained. The interactive image processing technique presented in this paper shows how simple digitisation of the experimental displacement fields may be obtained. A collection of these processed frames may then be combined to produce a 3-D time-displacement digital model of the experimental responses.

2 METHODOLOGY

2.1 *Experimental testing*

Samples for material testing were provided from the preserved cadaver of an adult leatherback turtle. A single tracheal ring was taken from above the bifurcation point and this was used to perform the test. The ring was fitted between flat plates on a Tinius Olsen H5 KS series material testing machine and compressed by 14.5 mm. Testing of the specimen complied with biomechanical standards and procedures. The trachea was preconditioned five times using a compression velocity of 5 mm/min. The sample was prepared in formaldehyde solution and the testing was performed at room temperature. Twelve red coloured paint markers were placed on both the inside and the outside edges of the specimen. These markers acted as a guideline to identify the boundaries of the trachea. As the analysis progressed the measured force, F_{exp}, was recorded. This provided a table of forces versus the corresponding displacement, Δ. The complete test was recorded using a digital video camera connected to the testing machine. Figures 1(a), 2(a), 3(a) and 4(a) show images of the trachea as it is being compressed at given times in the testing.

2.2 *Theoretical aspect*

An interactive program that allows the user to define the boundary geometry or 2-D experimental displacement fields of the material specimen through spline representation was developed using Microsoft Visual Basic.Net. The program imports a predefined series of frames from the experimental video and displays them one at a time on screen. These frames, which illustrate different positions of the specimen as it is being compressed, were saved as bitmap images after initial processing in MATLAB.

The user has the choice of which frame to work with at any stage. Using commands in the program, the user may select points on the boundary of the trachea using simple mouse left clicks. When the user is ready to fit a spline to the selected points, the right mouse button is pressed. At this stage a closed cubic B-spline is fitted to these selected

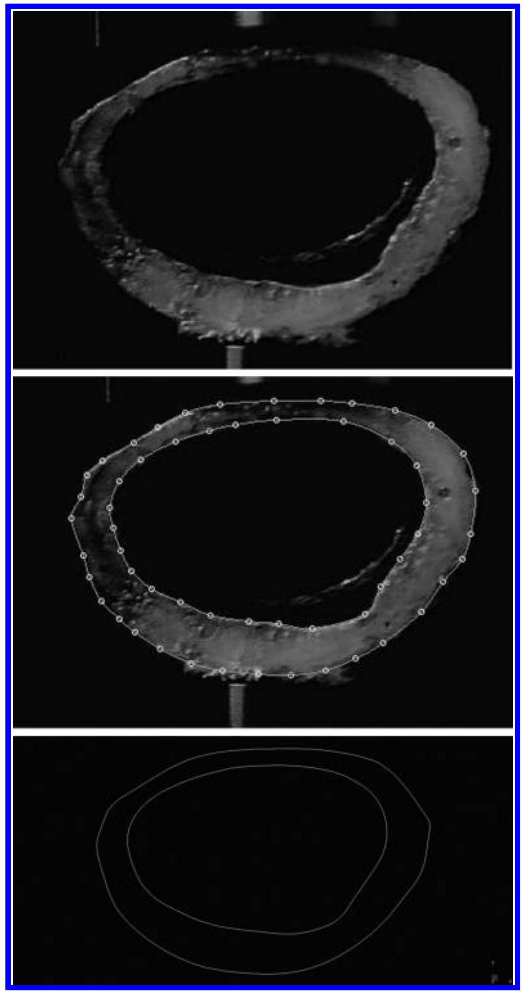

Figure 1. (a) [Upper] Trachea in initial position (t = 0 s) in the laboratory test. (b) [Middle] Screenshot of knots and spline fitted using VB.NET program. (c) [Lower] FE simulation of trachea at corresponding time.

points and displayed on screen. This procedure is repeated twice per frame, firstly for defining the outer boundary representation, and secondly for identifying the inner boundary representation. Once a spline has been defined, the user may move individual knots on the spline to a ‘better fit’ position.

When the user is ready to begin analysing another frame, the desired frame number is selected. The program identifies if any of the adjacent frames have splines fitted already. If true these splines are copied and imported onto the current frame. As these spline representations will be relatively close to the specimen position in the current frame, the user now just has to move the knots appropriately

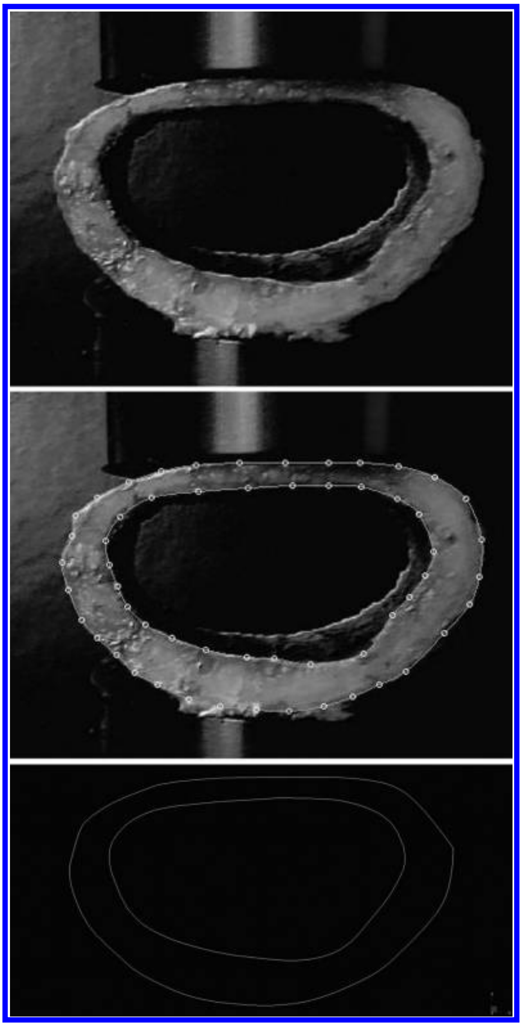

Figure 2. (a) [Upper] Trachea at time t = 40 s in the laboratory test. (b) Screenshot of knots and spline fitted using VB.NET program. (c) FE simulation of trachea at corresponding time.

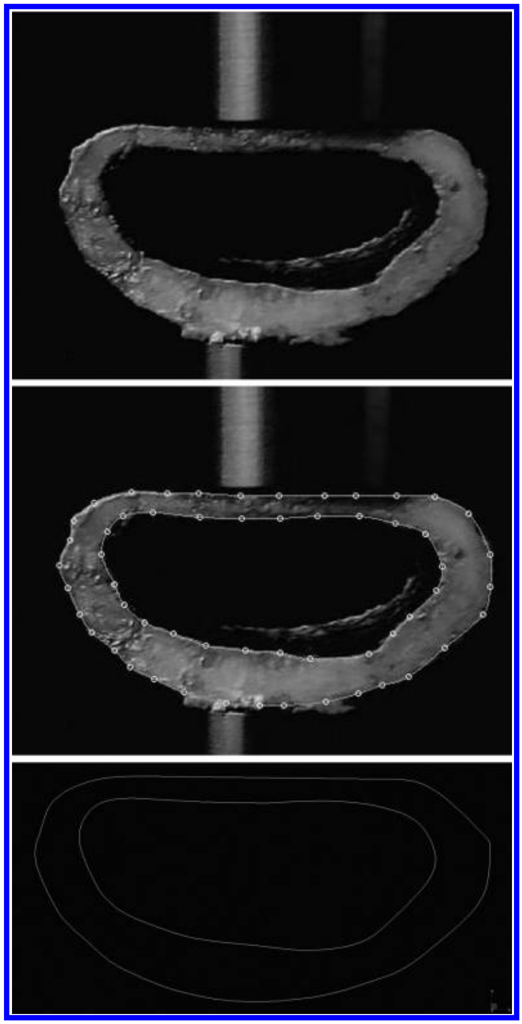

Figure 3. (a) [Upper] Trachea at time t = 90 s in the laboratory test. (b) [Middle] Screenshot of knots and spline fitted using VB.NET program. (c) [Lower] FE simulation of trachea at corresponding time.

to the correct position. This additional feature saves time in processing the images. If no splines have been created on neighbouring frames, the user simply selects points as before. Figures 1(b), 2(b), 3(b) and 4(b) show graphical representations of splines fitted on frames at the given times in the experimental testing.

As the inner and the outer spline boundary representations are being fitted for a given frame, the program creates a STEP Part 21 file (STP) for that frame at the same time. A STP file is a data exchange file that facilitates other programs in importing data representations. These files contain the geometric representation of the splines.

When the frames have been processed completely, they may be imported into a structural software package. In this study *Strand7*® is the software used. The STP files were imported into *Strand7*® individually for analysis. *Strand7*® assigns geometry to the 2-D displacement fields. This geometry was compared with the original bitmap image of the specimen. Using all of the frames, a 3-D time displacement digital model of the displacements was also created. The model was compared with the experimental video to assess the accuracy of the method. Figures 1(c), 2(c), 3(c) and 4(c) show the geometry of the spline representations that were imported into Strand7 at specified time in the test.

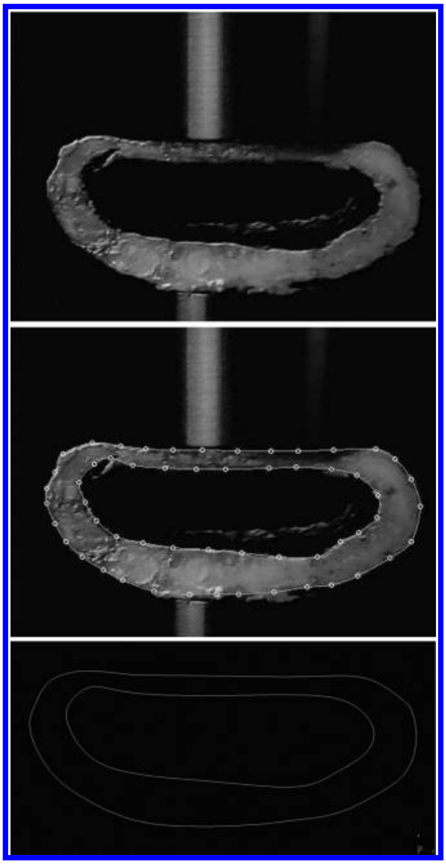

Figure 4. (a) Trachea in final position (t = 140 s) in the laboratory test. (b) [Middle] Screenshot of knots and spline fitted using VB.NET program. (c) [Lower] FE simulation of trachea at corresponding time.

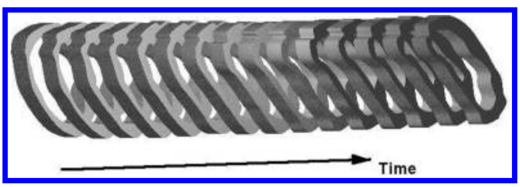

Figure 5. 3-D Time-Displacement digital model of the experimental responses.

3 RESULTS

Each of the Figures 1, 2, 3 and 4 compare the original images of the specimen taken during the experimental testing with the corresponding graphical spline representation created using the program in Visual Basic.Net and the corresponding 2-D geometric field that was imported into Strand7. Figure 5 depicts the 3-D time displacement digital model of the experiments responses.

4 DISCUSSION

This research demonstrates the feasibility of using image processing to determine a digital geometric representation of experimental displacement fields. It is shown that the image processing software facilitates easy digitisation of the experimental displacement fields. By means of a user friendly interactive program, accurate geometric representation may be digitised and imported quickly into structural and other analyses software with ease. This allows the user to continue with further analyses in a timely manner. The study presented in this paper arose from the need to classify the material parameters of the tracheal cartilage in leatherback turtles. Tracheal cartilage is a highly nonlinear material with irregular geometry. It has higher strength in compression than in tension. As a means of determining these parameters, an inverse methodology is currently being developed that will minimise the difference between theoretical FE simulations and experimental data using an unconstrained optimisation approach. The research sets out to characterise the material properties such that the difference between the experimentally measured responses (load and displacement history) and those from nonlinear FE simulations is minimised. The 3-D time displacement model developed in this paper will be combined with the FE model to compute an integral type objective which is to be minimised, i.e. that is an integral measure is set up that measures the difference between the simulated displacement field and the experimental generated displacement field. This is subsequently combined with the difference between the load histories to give a compound objective function that is then minimised with respect to the material properties. The material parameters in the FE model that minimises this objective function will then be assumed to be representative of the actual material parameters.

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Building information modelling

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BIM based manufacturing cost estimation of building products

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ABSTRACT: BIMs include nowadays detailed information of features of building products. Manufacturing costs of products can be estimated feature based, especially when considering steel products. The standard product models such as IFC and CIS2 have been developed during last 20 years to cover a lot of entities of BIM. Commercial cost estimation modules are available for product modelling software, but they are typically based on only preliminary information of products. In the paper is described a solution where a feature based manufacturing cost estimation module is integrated with a commercial BIM program. An example of comparing feature based cost estimation to rough weight based method is shown. Potential of presented method in design of steel structures both in basic and detail design phases are outlined in the paper. Also, future aspects for definition of even more accurate utilizing of product model in cost estimation are presented. In this phase only the manufacturing costs are dealt. Similar approaches are to be developed for estimating of transport and erection costs of buildings.

1 BACKROUND

1.1 *The feature based manufacturing cost estimation*

In feature based manufacturing cost estimation the entire assembly manufacturing process is split to single processes, whose cost structure is defined by modelling the process' individual cost elements. These elements may be based on, for example, time consumed or pre-calculated unit cost feature.

Feature of the product in this context is comprehended as attribute which causes cost. For example the colour of the coating is not a feature if it is included in the basic unit cost of the coating material. But if the specified colour adds cost compared with standard one, it is regarded as a feature. Features of the assembly, together with manufacturing line's fixed and variable costs, define the final cost of the assembly.

Feature based approach for steel building structures was presented by Watson et al. (1996), for batch production of light-weight steel assemblies by Schreve et al. (1999), for machined parts by Ou-Yang, C. & Lin, T.S. (1997), for steel frames by Pavlovčič et al. (2004), and for optimizing of composite and steel structures by Klanšek, U. & Kravanja, S. (2006).

Although method used by Watson et al. (1996) includes the entire cost of whole producing process starting from design and ending to erection, it uses discrete values for unit costs caused by features and is presented in prefilled spreadsheets. It gives the final cost of the structure but does not give information of the cause of the cost.

Models presented by Schreve et al. (1999) and Ou-Yang, C. & Lin, T.S. (1997) are based on time consumption of each single process of the manufacturing process. Both models are very detailed, but do not pay attention to the fixed or variable costs of workshop.

Pavlovčič et al. (2004) take into account raw material cost, consumable cost and manufacturing cost, but it is not clearly specified, what is included in manufacturing cost. Their model is based on time consumption, and covers the production chain from manufacturing to erection.

Klanšek, U. & Kravanja, S. (2006) consider material, power and labour costs, and their model covers the cost born in workshop only.

Also Farkas & Jarmai (2003) and Sawada et al. (2008) have presented functions for estimating the costs of single processes during the manufacturing process in workshop.

1.2 *BIM based cost calculation*

When aiming at cost effectively produced building structures, a special attention should be put on design phase. According to Evers & Maatje (2000) designer fixes 88% of the final costs by his design decisions. The main focus of the designer is to pay attention on resistance against forces but it could also be possible to advise the design based on cost information. In worst case no consideration is put on cost effects of the design selections.

Building Information Models (BIMs) include nowadays very detailed information of features of building products. This is especially true for steel structures and increasing for concrete and wood. Steel products are the main references in this study, but the methods presented are suitable for all building materials.

When using building information model it is possible to include in the model, even in basic design phase, such data that more accurate and detailed cost estimation is possible to achieve. To make the use of sophisticated cost model workable requires however a link between the building information model and cost model.

Commercial cost estimation modules are available for product modelling software, such as Virtual Construction for ArchiCad by Graphisoft (2010) and StruM.I.S for StruCad by Acecad (2010). However, these cost estimation modules are not based on so "deep knowledge" as required to calculate the costs of typical steel products of an industrial building as shown in Figure 1. It can be said, that these modules are based on "shallow knowledge", as defined by Tizani et al. (1996).

Based on referenced literature it can be argued that there is lack of suitable tools for cost estimation. Those on the market are mainly based on the mass of the structure, and do not give sufficient information for designer about cost variations of different design outcomes.

One specific problem is also that accurate cost estimation of different solutions is rather laborious if using manual transfer of design data between design and cost estimation software. The standard product models such as IFC (2008) and CIS2 Crowley & Watson (2000) have been developed during last 20 years to cover a lot of entities of BIMs. These are meant for BIM integrated solutions for many kinds of applications. Still the references where these standards are used to cost calculation are hard to found.

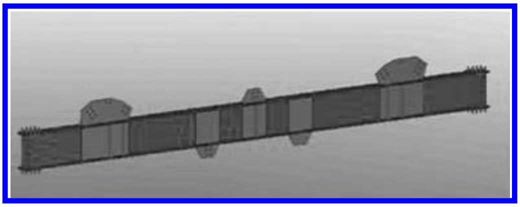

Figure 1. An example of a steel product of a building.

Generation of the general domain model will become more difficult, when detailed information is required. In this paper very fine-grained details of the whole building are considered. Still a professional knowledge from many areas is needed. Keeping this in mind, the solutions described for example by Isikdag & Underwood (2010), where the same model serves as well architects, HVAC-, as structural engineers, may be available far in the future.

Babič et al. (2010) have described some of the problems when BIM has been integrated to ERP systems. Their first demand is that the prefabricated elements (assembly) should be able to be composed from the design elements. In case described in this paper the problem is solved by the compatibility of modelling rules and data exchange program, which could very complicated in a general case.

The cost functions used in this study are originating from Haapio (2010). The prototype application was completed in a national research project "7D Design of steel structures" completed in Tampere University of Technology during 2007–2009.

2 THE CALCULATION OF MANUFACTURING COST

2.1 *The principles of the calculation*

When the designer compares the cost of different design solutions, he/she usually compares also the material cost against manufacturing cost. As the material is mostly purchased from outside the workshop, it includes already all the cost components. To get the comparison balanced we have to include all available cost components also to workshop costs.

A feature based cost estimation model for steel building skeleton is under development in Tampere University of Technology. In this model the manufacturing process of assembly is divided in single processes, which consist of blasting, cutting, beam welding, sawing, drilling, coping, fabrication of assembly parts, assembling, i.e. welding and bolting, post treatment, and painting. Each process is supposed to be executed in separate cost centre, with NC-driven equipment or manually in case of assembling and painting. Cost components included in the model are raw material, labour, investment cost of equipment and real estate, maintenance and service cost of equipment and real estate (including heating of the of the workshop space), cost of consumables such as welding wires, and energy cost of equipments.

Model takes into account both productive time, i.e. machining, and non-productive time, which includes additional works needed to execute the process, such as set-up of equipment, changing the tools, conveying the part in machine etc.

2.2 *The cost function*

Cost function of each cost centre is:

$$C_k = (T_{Nk} + T_{Pk})\ x\ (c_{Lk} + c_{Eqk} + c_{Mk} + c_{REk} + c_{Sek})/ u_k + T_{Pk}\ x\ (c_{Ck} + c_{Enk})$$

where

C_k = total cost of cost centre k [€]
T_{Nk} = non-productive time used in cost centre k [min]
T_{Pk} = productive time used in cost centre k [min]
c_{Lk} = unit labour cost of cost centre k multiplied by number of workers [€/min]
c_{Eqk} = equipment recovery unit cost of cost centre k [€/min]
c_{Mk} = unit cost of equipment maintenance cost of cost centre k [€/min]
c_{REk} = unit cost of real estate of cost centre k [€/min]
c_{Sek} = unit cost of service of cost centre k [€/min]
c_{Ck} = unit cost of time related consumables needed in processing of cost centre k [€/min]
c_{Enk} = unit cost of energy needed in processing of cost centre k [€/min]
u_k = utilization ratio of the cost centre k [real, ≤1]

Functions for calculation of times T_{Nk} and T_{Pk} include parameters and variables. Parameters are pre-set according to best known information of workshop environment, such as cutting speed. Variables are selected so, that they can be determined by designer during modelling wherefrom they are transferred to the cost estimation model as described in further chapters.

Unit costs of cost centre k are also set in advance. These contain workshop depended cost, such as cost of equipment, cost of real estate, and floor area needed for single process. Both parameters and unit costs are possible to fine tune when manufacturer is chosen and his environment is known.

3 TEST ENVIRONMENT

3.1 *The modules of the environment*

To see how the costs are behaving in different cases a test environment was required. To have a flexible solution a modular structure of it was determined. The environment was divided into the following parts: 1) BIM produced by commercial software, 2) data exchange program from model to cost calculation, 3) cost database and 4) cost calculation functions. In Figure 2 has been shown the structure of environment with the steering information of the modules.

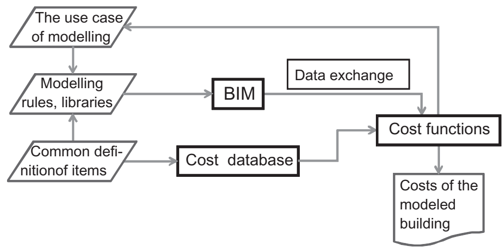

Figure 2. The test environment.

When methods are developed and different functions tested it is important that the functions can be easily edited. Then they cannot be hard-coded to one commercial program. In the same way the cost database of materials, labour and investments should be able to be tuned without changes to other modules. The different users may have different cost databases for same cost elements.

The modelling software Tekla Structures was selected. Versions 14.1 and 15.0 were used. The selection was made based on the availability of the support to the programming interface. The programming was needed because of data exchange. Any of the standard files had all of the needed attributes, or the considered modelling software did not support them. For example CIS2 includes all the features needed in this study, but it was not possible to apply, because weld entities were not implemented into the transfer from the considered BIM software. The written program reads the data from the model and writes it to the clear text format.

The cost calculating functions were written to the MS Excel program. The calculations could easily be varied because input values could be updated by the interface of this software. The weakness of that environment was its limits to the amount of data. In the text file there are own lines for example from every different welds to every different assembly. From the complete industrial establishment over 60000 lines could be output which is much to used software. Also the calculation time will arise when there are several tens of thousands lines to be read. A genuine database would have been more effective but in the selected solution the modifications can be done within one program.

Also the cost database was added to the same Excel file. The own unit cost format was used instead of any standard. If the lists would have been read from other sources the change of them could have been easier. The on-line price lists, through for example the internet, were not available.

If the cost output is required in Euros, all cost input has to be updated values. By outdated costs the different cases can still be compared to each other if the relationships between prices are still right. This rule will not realize if for example the price of the energy will rise relatively more than other costs.

3.2 *Requirements to the BIM and data exchange*

The idea of using BIM as the source of information of cost calculation is that the manufacturing costs can be calculated from the final geometry and attributes of the building parts. Then the accurate modelling of joints is in important role because remarkable part of the manufacturing costs results from joint fabrication as told for example by Nethercot (1998) and Girardier (1995).

The joints could be composed from the several small parts and assembly processes, like welding. If the costs of one joint are wanted to calculate all the parts of the one joint should be able to group together. Then for example the cost effect of different joint types can be compared. As told before in the calculation of cost one joint is handled only as a group of parts and processes. Any other way to save the joint information has not been used.

The parts should further be grouped to the assemblies which represent the prefabricated wholeness's. Then the cost calculation can be divided by the same way. To one assembly can be included several parts.

If all supposed data has not been modeled it can be completed by special programs adding some solution to the model. That method is difficult when an own program is needed to every different type of structural parts. The solution selected here was that to every input attribute, read from the model, it is possible to give a default value. For example if unit cost of IPE beam is not found from the cost database the default unit cost [€/m] is calculated from the weight [kg/m] of the part and default unit cost of steel material [€/kg].

3.3 *Content of the data output from the BIM*

The developing of environment was started by analyzing the cost estimation functions. From the input values of them were separated all the data which can be read from the BIM. The hierarchical aggregation form of data is described in Figure 3. From the data the modelling rules mentioned in Figure 2 were determined.

In hierarchy even a single and disjointed building part should be modeled as an assembly. From each assembly the identifier and the number of similar ones are output.

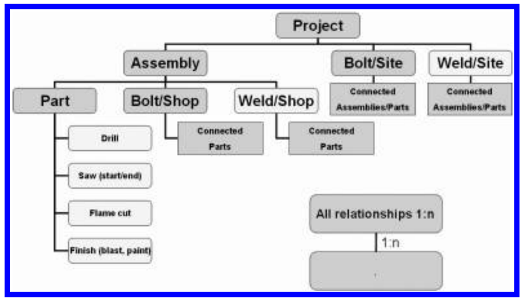

Figure 3. The relationships of data output from the BIM.

Below an assembly all the parts included to it are listed. Also from the parts the identifier and the number of similar ones are output. From the normal parts this information was also output: profile, material, length, weight, area and painting system. The character type information about the profile and material must be match to the cost database as shown in Figure 2. Own lines for different materials of the same profile could have been included to the cost database. The method used here was to use only one unit cost for one profile. The unit cost was changed by a coefficient depending on material.

The character type information about finish should be match to the work list in question. To the work is given the labour and material cost. In test cases only painting cost were recognized. Used method does not notice if some face of the profile, for example the top, is not painted. An optional painting system was able to use if finishing was not given or not recognized. To make an exception from this rule a special key word to painting system could have been used.

Plates, from which three dimensions are output instead of length, have been separated from normal parts. In cost calculation there is an option if the parts will be sawed to the right dimension or not. For that purpose the possible sawing angle is an output from model.

To every part the dimension of every different size of holes with the number of them are output.

All the cuts made to the part are output separately. The cuts are supposed to be done by flame cutting. In the programming interface of the modelling software the available information about cuts was the cross section of the cutting object. Those measures were used to cost calculation even they may not be exactly the right ones depending how the cut is done in the BIM. Also a single hole without a bolt may have been modeled as a cut. To have more accurate results the modelling of cuts should be more controlled.

For welded profiles, which have been composed of plates having different thicknesses, the input of plate thickness is not included for cutting cost calculation. Instead the largest value of the profile plate thicknesses has been used. Thus the calculated costs will be upper boundary.

By the concept of assembly it can easily be ensured that the parts of one joint are calculated only once. Then also the possible extra parts in the model will not be included. The exceptions to this rule are bolts and welds which are to be assembled at the site, thus not modeled to workshop assembly.

From bolted joint bolt type, size, cut length, grade, nut type, number of nuts, washer type and number of washers are output. If the type information does not match to the cost database a default unit cost can usually be used to these small parts. One bolt needs holes to the several parts. Every hole is associated only to the part.

From welds the type, size and length information is output. Unfortunately from this information the accurate manufacturing costs cannot be calculated because the cost of welding is depending on the position of the assembly during welding. The welding done upwards is very expensive compared to optimum position. The mean cost of welding is used.

In some workshops it could be possible to rotate the object during welding so that the position is always best possible. But as the rotating cause's costs, the most cost effective welding position does not necessarily always give the lowest total cost result.

From the bolts and welds assembled at the site the same information is output to the end of the file. The costs of them cannot be calculated belonging to any joint if that information is not included in the model. In this case that information was available.

All other data needed in cost calculations were given by the Excel tables. This kind of information is for example the values describing the productivity of the blasting, sawing and drilling machines in the workshop or the drying times of different kind of painting systems.

4 THE TEST CASES

In the first case the application ability of the developed cost estimation environment was tested. Within minutes almost 60000 entities were recovered from the model. The BIM of first erection block of the boiler plant shown in Figure 4 was the input.

Second example illustrates how the designer can estimate the joint costs in the basic design phase. Three joints presented in Figure 5 were designed so that they have the same shear force resistances which were calculated using the program CoP documented by Jaspart et al. (2005). Columns and beams are the same in all joints.

The relative costs differences for the joints are: Fin plate joint 100, End plate and Cleat joint about 120. The cost of cleat joint depends on the drilling techniques. If the automatic drilling line is available in the workshop then the cost factor of the cleat joint is about 110. The factor 120 for the cleat joint is the mean of using either automatic drilling line or manual drilling. If the designer do not know what kinds of process lines are available in the workshop, then the mean values can be used for the estimation. When the manufacturer of the assemblies is known, then the designer or the manufacturer can use the proper values for the processes in the workshop and justify the cost effects and search for the better solution taking into account the manufacturing resources, of course in co-operation with the designer.

The third example is given in details in Heinisuo & Jalkanen (2009). In that study the manufacturing costs of the minimum weight column was 1455 Euros and the cost of the minimum cost column was 1309 Euros.

Fourth example demonstrates the optimum design of the steel beam when the manufacturing costs of the joints at the beam ends are taken

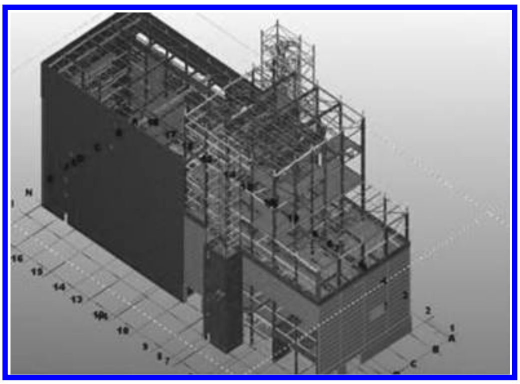

Figure 4. Part of boiler plant to test the application ability of cost calculation.

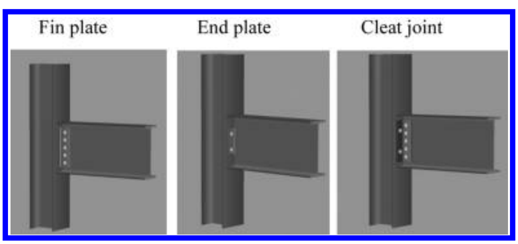

Figure 5. Fin plate, end plate and cleat joints.

into account. Detailed calculations are shown in Haapio & Heinisuo (2010). The design space was:

– symmetric IPE beams available, steel material grade S235,
– grade S235 steel plates available for the joints,
– bolts of grade 8.8 available for the joints,
– end plate joints should be used.

The constraints were the requirements in ambient conditions following the EN standards. The result with the uniform design load 33 kN/m and the beam span 5 m was, that if the costs of the beam with semi-rigid joints is 100, then the costs of the beam with rigid joints is 116 and with the hinged joints 142. Similar results are given in the literature for entire frames Anderson et al. (1987), Grierson & Xu (1992), Simoes (1996).

5 DISCUSSION AND CONCLUSIONS

The prototype program to estimate the manufacturing costs based on the feature information got from the commercial BIM software was developed. Steel structures were the references in this study, but the method developed can be used for any kind of structures. In the tests the developed system seemed to manage well also rather large models.

Cost functions for the processes needed in the manufacturing process are available in the literature. The BIMs include very detailed information of the products thus the availability of information requires the modelling rules. Still it could be assumed that rather accurate cost comparison between different solutions can be done in the future at every design phases, including very preliminary design. This is possible due to fact, that especially for steel structures the macros for joint detailing are available in the commercial BIM software enabling quick changes of joint layouts and see the effect to the costs. In steel structures the costs originating from the fabrication of joints are essential.

The economical risks can be reduced at all stages of the project using the developed system. The product model data is becoming more and more detailed during the project. So the main contractor can use the method for his/her scope, as well subcontractors for their products. The reliability of the cost estimation depends on the cost functions and the basic cost data for materials, real-estates, energy etc. In the prototype the data for these are those available in the literature. The companies can put their own information to the cost functions and to the basic cost data, so they can use the system just for their own manufacturing process.

In this study only the manufacturing costs were handled. In ongoing development work also the entire production chain costs including design, transportation and assembly installation (erection) are to be included in the cost estimation model. Especially erection cost is believed to have a strong dependency with chosen structural details.

When considering the welding of all the plates of the assembly shown in Figure 1, then arises the question of the optimum position of the assembly for welding. It is believed, that using the developed system integrated into the process simulation and its optimisation, new cost effective solutions may be found in the future.

6 DEFINITIONS

Assembly	=	product coming out from workshop doors
Cost centre	=	area in workshop to execute a specified process. Cost centre's features are: floor area, equipment needed for process and number of workers
Fabrication	=	fabrication of a part
Manufacturing	=	sum of fabrications, resulting an assembly
Part	=	single entity assembled to the assembly
Process	=	activities needed to produce a single feature

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Towards spatial reasoning on building information models

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ABSTRACT: The paper presents a conceptual study on the application of spatial reasoning on building information models. In many cases, building regulations and client demands imply constraints on the building design with inherent spatial semantics. If we are able to represent these spatial constraints in a computer-interpretable way, the building design can be checked for fulfilling them. In this context, spatial reasoning technology can be applied in two different ways. First, we can check the consistency of the spatial constraints in effect, i.e. find out whether there are contradictions between them. Second, we can check whether a concrete building design is compliant with these constraints. The paper gives a detailed overview on the currently available spatial calculi and introduces two possible implementation approaches.

1 INTRODUCTION

The architectural and structural design of buildings is a complex task where numerous rules have to be taken into account. These rules reflect technological constraints, national regulations and client demands. Among them spatial rules play an extraordinarily important role, since the objects to be designed are of intrinsic geometric nature.

To better support engineers and architects in the design process, it is desirable to create software applications which are able to check a concrete building design against the aforementioned rules. Significant scientific results have been achieved for formalizing and checking rules which are based on a comparison of alphanumeric values of individual attributes, such as the thickness of a house's outer walls or a slab's thickness (Ding et al. 2006, Kim & Grobler 2009, Nisbet et al. 2009).

However, the possibility to define and check rules which comprise qualitative spatial relationships between building components (such as *above, below, touch, within* etc.) has been investigated only by few researchers. A first approach for implementing spatial constraint checking technology on the basis of a spatial constraint language has been presented in (Borrmann et al. 2009). However, a main issue remained unsolved: If there are contradictions between different spatial constraints, the solution space for a valid building design may be empty. This has to be detected before the architect or engineer starts trying to fix his design, complying with one rule and violating another in an endless loop.

This paper presents a concept on how spatial reasoning technology can applied to resolve this issue. Computational reasoning in general is a well-known technology for (1) deriving new knowledge from existing facts by the application and concatenation of rules and (2) checking the consistency of these rules. Spatial reasoning, in particular, provides the possibility to derive new knowledge regarding spatial relationships between objects and to check the consistency of spatial constraints.

2 RELATED WORK

A very important application of formalizing and checking constraints in the context of building information modelling is *Automated Code Checking*. Here, the vision is to encode regulations and building design codes in a computer-interpretable way such that the digital building can be checked against these rules (Han et al. 1997). The International Code Council (ICC) has started to work intensively in this direction and has created the SmartCodes initiative (Nisbet et al. 2009).

Ding et al. have implemented the Australian disabled access code on the basis of IFC models (Ding et al. 2006). In their approach, first a simplified model is created from the IFC model by applying an EXPRESS-X mapping. In a second step, building codes are encoded into object-based rules using the EXPRESS-based rule schema.

A suitable basis for reasoning on high-level concepts, such as the semantic (non-spatial) part of a building information model, is an ontology. In general, an ontology is defined as a "formal specification of a shared conceptualization" (Gruber 1993). More precisely, it is used to capture the semantics of a domain's concepts and the relationships among them.

Using the Ontology Web Language (OWL), standardized by W3C, an ontology can be formally specified. OWL distinguishes classes, properties and instances, comparable to the object-oriented paradigm. Additionally, OWL provides property characteristics (*transitive, symmetric, functional, inverse*) and property restrictions (*allValuesFrom, someValuesFrom*) as well as *is-a* relationships with generalisation/specialisation semantics.

There are three language flavours of OWL (Lite, DL, and Full). The one relevant for the work presented here is OWL DL (description logic), which is based on the logic SHOIN(D) (Horrocks et al., 2003). It provides a maximum expressiveness while retaining computational completeness, decidability, and the availability of practical reasoning algorithms. Beetz et al. (2009) show how the Industry Foundation Classes (IFC), the most mature and well established data model for building information models can be transformed into an OWL ontology. The resulting IfcOWL ontology forms part of the concept presented in Section 3.

In (Kim & Grobler 2009) an ontology-based approach is presented for representing requirements and constraints of a project. The authors propose to employ an ontology reasoning mechanism to detect conflicts between diverging participants' requirements in collaborative design scenarios. Unfortunately, the paper discusses only very basic quantitative constraints, such as limits on a slab's thickness.

The work closest to the approach presented in this paper is (Bhatt et al. 2009) where spatio-terminologic inference has been applied for the design of ambient environments. The authors employ the reasoning engine RacerPro which supports spatial representation and reasoning based on the Region Connection Calculus (RCC, see Section 4). Besides that, the IFC data model is applied for terminological representation and reasoning. However, the presented spatial reasoning approach is restricted to 2D space and directional relationships are not taken into account.

3 CONCEPT

The application of computational reasoning technology can help to facilitate the design task and support the designing architects and engineers. There are two important applications of inference techniques in the context of building design and engineering. The first application is the detection of contradictions between individual requirements and/or regulations, i.e. checking the consistency of all effective constraints. The second one is to check a concrete building information model for compliance with the client's requirements or with certain regulations.

3.1 *Application 1: Constraints consistency checking*

A simple example for inconsistent spatial constraints would be the following:

- C1: "The heating equipment must be within Room1."
- C2: "Room2 must be directly above Room1."
- C3: "The heating equipment must not be directly below Room2."

For real world projects, the network of spatial constraints is much more complex and detecting inconsistencies between them is very difficult. Here, the application of spatial reasoning technology can significantly support the architects and engineers. To verify the consistency of the spatial constraints, a reasoning engine supporting spatial calculi is applied.

3.2 *Application 2: Compliance checking*

For checking a concrete building model for compliance with the effective spatial constraints, qualitative spatial relations between individual building components are required as facts. They can be retrieved using the Spatial Query Language presented in (Borrmann & Rank 2010). Using the Spatial Query Language, we can automatically identify the spatial relationship holding between any two building components. This includes topological and directional relationships.

The resulting set of spatial facts can then be checked for compliance with the effective spatial constraints representing regulations, client demands, or construction rules. Here again, a reasoning engine can be applied, in this case to prove the consistency of the instance population with the spatial constraints in effect.

4 SPATIAL CALCULI

The basis for any formal reasoning is a *calculus.* A calculus is a system of rules which allows to derive new knowledge from given facts (axioms) in a logically consistent way. This process is called inference.

In the domain of spatial reasoning different qualitative properties of and relations between spatial objects are of interest, including topology, orientation, shape, size and distance.

To allow reasoning, a suitable qualitative representation of facts is necessary, i.e. continuous properties have to be mapped to a discrete set of symbols. Moreover, these symbols have to meet the requirement that represent *Jointly Exhaustive and Pairwise Disjoint* (JEPD) facts. In the next subsections we will have a closer look on available calculi for topological and directional reasoning.

4.1 *Calculi for topological reasoning*

The Region Connection Calculus (RCC) is the most established calculus for topological reasoning. Since RCC also covers part-whole relationships between objects, it is also referred to as mereo-topological calculus (Randell et al. 1992). It has been designed for reasoning on regions in *n*-dimensional space, a region being defined as a set of points delimited by a continuous boundary curve.

The RCC-8 version defines eight different topological relations between two regions:

– *Disconnected* (DC),
– *Externally Connected* (EC),
– *Partial Overlap* (PO),
– *Equal* (EQ),
– *Tangential Proper Part* (TPP) and its inverse (TPPi),
– *Non-Tangential Proper Part* (NTPP) and its inverse (NTPPi).

These different relations are illustrated in Figure 1.

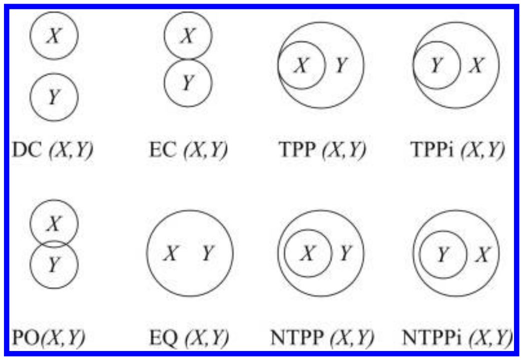


Figure 1. The eight topological relationships defined by RCC-8.

o	DC	EC	PO	TPP	NTPP	TPPi	NTPPi	EQ
DC	*	DC,EC,PO, TPP,NTPP	DC,EC,PO, TPP,NTPP	DC,EC,PO, TPP,NTPP	DC,EC,PO, TPP,NTPP	DC	DC	DC
EC	DC,EC,PO, TPPi,NTPPi	DC,EC,PO, TPP,TPPi,EQ	DC,EC,PO, TPP,NTPP	EC,PO,TPP, NTPP	PO,TPP, NTPP	DC,EC	DC	EC
PO	DC,EC,PO, TPPi,NTPPi	DC,EC,PO, TPPi,NTPPi	*	PO,TPP, NTPP	PO,TPP, NTPP	DC,EC,PO, TPPi,NTPPi	DC,EC,PO, TPPi,NTPPi	PO
TPP	DC	DC,EC	DC,EC,PO, TPP,NTPP	TPP,NTPP	NTPP	DC,EC,PO, TPP,TPPi,EQ	DC,EC,PO, TPPi,NTPPi	TPP
NTPP	DC	DC	DC,EC,PO, TPP,NTPP	NTPP	NTPP	DC,EC,PO, TPP,NTPP	*	NTPP
TPPi	DC,EC,PO, TPPi,NTPPi	EC,PO,TPPi, NTPPi	PO,TPPi, NTPPi	PO,TPP, TPPi,EQ	PO,TPP, NTPP	TPPi,NTPPi	NTPPi	TPPi
NTPPi	DC,EC,PO, TPPi,NTPPi	PO,TPPi, NTPPi	PO,TPPi, NTPPi	PO,TPPi, NTPPi	PO,TPP, NTPP,TPPi, NTPPi,EQ	NTPPi	NTPPi	NTPPi
EQ	DC	EC	PO	TPP	NTPP	TPPi	NTPPi	EQ

Figure 2. Composition table of the Region-Connection Calculus (Randell et al. 1992).
* denotes the universal relation.

The RCC-8 reasoning allows to derive from the given information on the topological relation *R1* between two objects *A* and *B* and the relation *R2* between two objects *B* and *C*, the topological relationships *R3* between the objects *A* and *C*. The inference process is realized by applying the composition table shown in Figure 2. For explaining the usage of the table, we suppose that the relation *EC* holds for objects *A* and *B* and *NTPP* for objects *B* and *C*. Using the table we can derive that for *A* and *C* the relation *DC* must hold.

When restricted to simple plane regions, RCC-8 is equivalent to the 9-Intersection Model (Egenhofer 1991), a very influential model in the GIS domain.

4.2 *Calculi for directional reasoning*

Direction is a binary relation of an ordered pair of objects *A* and *B*, where *A* is the reference object and *B* is the target object. The third part of a directional relation is formed by the reference frame, which assigns names or symbols to space partitions.

In a geographical context, we usually distinguish four (*north, east, south, west*) or eight space partitions (*north, north-east, east, south-east, south, south-west, west, north-west*). In 3D context, normally the additional directional predicates *above* and *below* are used, which may also be employed in conjunction with the aforementioned 2D sub-direction, resulting in *north-east-above*, *east-above*, etc.

For directional reasoning in two-dimensional space, Frank (1992) has defined two models for defining directional relations between points: the cone-based and the projection-based model. The cone-based model dissects the space around the reference point in either four partitions of 90° or eight partitions of 45° (Figure 3, left-hand side). The direction of the target point with respect to the reference point is defined by the partition in which the target point is located. Figure 4 shows the composition table for the four-partitions case. From the total of 25 different combinations, one can only infer 13 cases exactly and four approximately (lower case letters indicate approximate reasoning).

The projection-based model (Frank 1992) dissects the space by means of horizontal and vertical lines that cross at the reference point (Figure 3, right-hand side). While the horizontal line creates

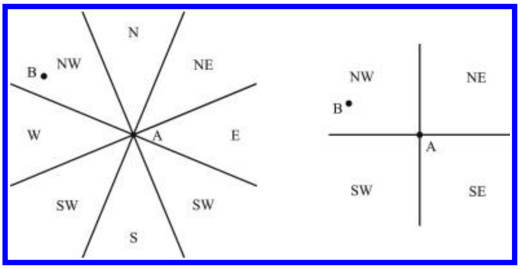


Figure 3. Frank's cone-shaped (left) and projection-based (right) models of directional relationships between points.

	N	*E*	*S*	*W*	*O*
N	*N*		*o*		*N*
E		*E*		*o*	*E*
S	*o*		*S*		*S*
W		*o*		*W*	*W*
O	*N*	*E*	*S*	*W*	*O*

Figure 4. Composition table for four cone-shaped directions (Frank 1992). *O* denotes the identity relation, i.e. both objects having the same position. Lower case letters indicate approximate reasoning.

	N	*NE*	*E*	*SE*	*S*	*SW*	*W*	*NW*	*O*
N	*N*	*N*	*NE*	*e*	*o*	*w*	*NW*	*NW*	*N*
NE	*NE*	*NE*	*NE*	*e*	*e*	*o*	*NW*	*n*	*NE*
E	*NE*	*NE*	*E*	*SE*	*SE*	*s*	*o*	*n*	*E*
SE	*e*	*e*	*SE*	*SE*	*SE*	*s*	*s*	*o*	*SE*
S	*o*	*e*	*SE*	*SE*	*S*	*SW*	*SW*	*w*	*S*
SW	*w*	*o*	*SE*	*SE*	*SW*	*SW*	*SW*	*w*	*SW*
W	*NW*	*n*	*o*	*SE*	*SW*	*SW*	*W*	*NW*	*W*
NW	*NW*	*n*	*n*	*o*	*w*	*w*	*NW*	*NW*	*NW*
O	*N*	*NE*	*E*	*SE*	*S*	*SW*	*W*	*NW*	*O*

Figure 5. Composition table for the projection-based model (Frank 1992).

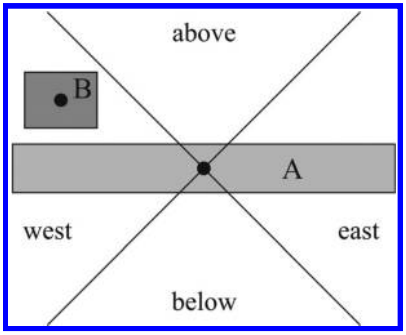
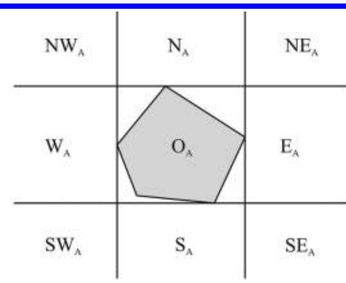


Figure 6. Approximating target and reference object by their centroids may cause results that do not comply with the intuitive expectations of the users. In this example, *B* is classified as being west of *A* and not as being above it.



$$\mathbf{dir}_{RR}(A,B) = \begin{bmatrix} NW_A \cap B & N_A \cap B & NE_A \cap B \\ W_A \cap B & O_A \cap B & E_A \cap B \\ SW_A \cap B & S_A \cap B & SE_A \cap B \end{bmatrix}$$

Figure 7. In the CDC, a 3×3 matrix is used to capture the relationship between the reference and the primary object.

a northern and southern halfspace, the vertical line creates the western and eastern halfspace. Superimposing the halfspaces produces four directional partitions, namely *north-west, north-east, south-east* and *south-west*. The composition table for the projection-based model is depicted in Figure 5.

These calculi are defined only for point-point relationships in 2D space. In the context of building information modelling, however, we mainly deal with extended objects in 3D space. In order to apply the available models on extended 3D objects, a point-based approximation, such as the center of gravity, is normally used. However, this rough approximation often causes results that do not comply with the intuitive expectations of the user (Figure 6).

Only few calculi are available for directional relationships of extended objects. One of them is the Rectangle Algebra (Balbiani et al. 1999) which approximates both the reference and the primary object by their bounding boxes. Another one is the Cardinal Direction Calculs (CDC) introduced in (Goyal & Egenhofer 1997) for representing directional relations between connected regions. In CDC, the reference object is approximated by a box, while the primary object remains un-approximated. The bounding box of the reference object forms nine direction partitions. For representing a directional relationship, a matrix is employed that captures which of these nine partitions is covered by the primary object (Figure 7). Out of the 512 possible matrix assignments, only 218 exist in reality—they form the basic relations of the calculus. Figure 8 depicts one of these relations as an example.

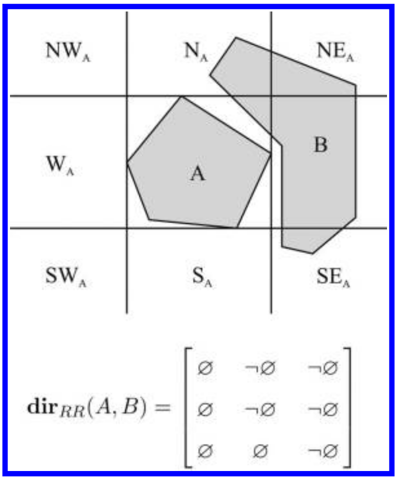


Figure 8. An example for a directional relation between the objects A and B.

In (Zhang et al. 2009) an efficient algorithm for checking consistency of basic CDC networks has been introduced.

4.3 *Calculi combining topological and directional relations*

Only few works are known which combine topological and directional relationships in one calculus. Among them is (Sun & Li, 2005) which combines RCC-8 with the Cardinal Direction Calculus, and (Li 2007) which combines RCC-8 with the Rectangle Algebra.

5 TECHNICAL IMPLEMENTATION

5.1 *Option 1: Using a hard-wired spatial reasoner*

One possible option for the technical realization of the presented concept is the application of a reasoner with hard-wired capabilities for spatial reasoning. One example is the reasoning engine RacerPro which provides reasoning over ontologies (TBox) and their instances (ABox) as well region-based spatial reasoning by the so-called S-Box. Using Racer Pro, we can represent the building information model on the one hand as semantic model according to the IfcOWL ontology. This part is stored in the TBox and ABox, respectively. On the other hand, spatial knowledge on the building model can be derived from the 3D geometry representation using the spatial query language developed by the authors. Figure 9 depicts this concept. Links can be established between the ontological objects of the ABox and their spatial representation in the SBox, allowing for combined spatio-ontological reasoning.

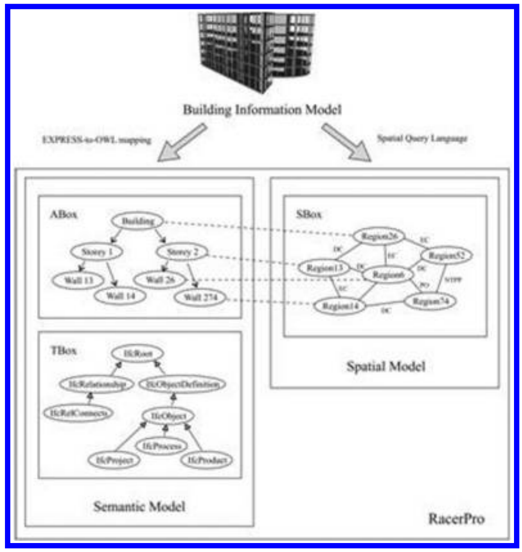


Figure 9. From the building information model, information for the semantic reasoner (ABox) and the spatial reasoner (SBox) is derived.

The spatial constraints to be applied can be expressed as facts of the SBox. Its reasoning capabilties can then be used (1) to check the consistency of these constraints, and (2) to check compliance of the spatial objects with these constraints.

The advantage of this implementation approach is its comparatively easy realization, since the desired spatial reasoning technology can be used out-of-the-box. On the other hand, the RacerPro's S-Box provides only reasoning on topological relationships, reasoning on directional relationships is not possible.

5.2 *Option 2: Using an extensible reasoner*

Another implementation approach is the application of a reasoner which provides the possibility for a flexible integration of arbitrary spatial calculi. One example for such an extensible reasoner is the SparQ toolbox, which supports binary and ternary spatial calculi (Wallgrün et al. 2007). A new calculus can be specified using a LISP-like syntax. For any defined calculus SparQ provides the following reasoning functionalities:

- qualification (turning a quantitative geometric scene description into a qualitative one)
- computing with relations
- constraint reasoning.

The latter refers to solving Constraint Satisfaction Problems (CSP) modeled as constraint graphs; these are complete labeled graphs with a node for each spatial object (also denoted as variable) and each edge labeled with a relation from the calculus. A CSP is consistent, if an assignment for all variables can be found that satisfies all the constraints.

The SparQ toolbox is able to detect inconsistencies of a constraint graph, which in our case can be applied for realizing application scenario 1. The toolbox is also able to 'heal' the constraint graph by removing one or more constraints. For concrete spatial objects, the 'scenario consistency' can be checked (Application 2).

Unfortunately, the provided reference implementations for spatial calculi are exclusively for reasoning about the orientation of point objects or line segments. The available calculi include Allen's Interval Algebra (Allen 1983) and Freksa's Double Cross Calculus (Freksa 1992) among others. An implementation of RCC-8 is unfortunately not yet provided.

The advantage of using an extensible spatial reasoner is the great flexibility of this approach. In principle, any of the available spatial caluli can be integrated. However, the implementation effort should not be under-estimated.

6 DISCUSSION & FUTURE WORK

The paper has introduced a concept for enabling spatial reasoning on building information models. There are two important applications of spatial reasoning in the context of building design and engineering: (1) detecting contradictions between the effective spatial constraints and (2) checking a concrete building information model for compliance with the effective spatial constraints.

The paper has discussed in detail available spatial calculi which form the basis for spatial reasoning. The Region-Connection Calculus (RCC) enables reasoning on topological relations between *n*-dimensional regions. Frank's directional calculi enable reasoning on directional relationships, but only between points. An alternative model for expressing directional relationships between extended objects is the Cardinal Direction Calculus by Goyal and Egenhofer.

The paper has further discussed two different implementation concepts. The first one is based on the application of a reasoning engine with hardwired support for reasoning using a specific spatial calculus. The second one is based on employing reasoner which can be extended by any form of spatial calculus.

The authors see a high potential in using spatial reasoning technology for building information models and will continue their work on this topic. The next steps will be:

– Find suitable calculi for spatial reasoning on building information models. It will be of special importance to investigate which of the available calculi can be applied on extended 3D objects. If suitable calculi are not available, emphasis has to be placed on developing them.
– Experiment with both implementation approaches and decide for the more appropriate one.
– Ensure compatibility between the "spatial facts" about a specific building model generated by applying the spatial query language and the chosen calculus.
– Create a prototypical implementation. Derive a set of spatial constraints from client demands and regulations. Check concrete building models for compliance with these constraints.

It will be a long road of research and development towards realizing spatial reasoning on building information models, but the authors are happily facing this challenge.

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4D modelling of large industrial projects using spatio-temporal decomposition

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ABSTRACT: There has been a growing interest in the emerging technology of four-dimensional modelling and planning of industrial projects. In comparison with traditional 3D CAD and project management systems, 4D modelling provides for more comprehensive visual analysis of the projects. As free and commercial applications are becoming more accessible, numerous attempts to employ it in different industrial domains and programs are undertaken. Nevertheless, most applications are faced with the fundamental problem of the performance degradation at large-scale projects. In this paper we discuss an approach to 4D modelling using spatio-temporal decomposition and providing special facilities to effectively access project data and to execute typical requests relevant to given time and space domains. Three partitioning schemas are presented and analysed to satisfy performance requirements. The schemas exploit peculiarities of spatial and temporal coherence of pseudo-dynamic scenes appearing in 4D modelling and planning applications. Theoretical complexity estimates are given to prove the suitability of the schemas for efficient modelling of large industrial projects.

1 INTRODUCTION

Since the early 1990s, there has been a growing interest in the emerging technology of four-dimensional modelling of industrial projects (GSA BIM 2009, Heesom & Mahdjoubi 2004). In comparison with traditional CAD and project management systems, 4D modelling provides for more comprehensive visual analysis of the projects. Importantly, it assumes not only aesthetic visualization of the project phases, but also multifactor planning and scheduling of the projects. Its major benefits are as follows:

- improved communications among stakeholders due to the simulation of project activities ‘in progress’ and their immediate visualization as elements of dynamic scenes;
- trustworthiness of project schedules carefully evaluated and verified against potential spatio-temporal clashes;
- optimum use of critical resources taking into account not only temporal, but also a spatial factor. In particular, it assumes improved logistics at the project site.

In final respect, 4D modelling enables better planning and helps to identify and remove errors at the earlier phases of design and planning, reducing potential waste during project realization. Providing a commonly shared vision of design intent, project plan and its current status, the technology eliminates misunderstanding among stakeholders and promotes to the project success (Sriprasert & Dawood 2002, Retik 1993).

As free and commercial applications like Synchro, EuroSTEP 4D Linker, VirtualSTEP 4D Planner, Bentley Schedule Simulator, Intergraph Schedule Review, Autodesk NavisWorks, Common Point Project 4D, Visual Engineering VPS, VTT 4D CAD, CSA PMvision, Domos 4D-suit are becoming more accessible, numerous attempts to employ the technology in different industrial domains and programs are undertaken (Seliga 2007).

Nevertheless, most applications are faced with the fundamental problem of the performance degradation for large project data consolidating huge 3D models and detailed scheduling information. The structural hierarchical decomposition of a whole project into subprojects, work breakdown structures and activities can be adopted as an effective approach to scheduling theory problems. However, it is not well suited for such computationally intensive problems as ray tracing, collision detection, motion planning usually carried out during 4D modelling sessions.

Octrees, k-d trees, BSP-trees, BRep-indices, tetrahedral meshes, and regular grids are all examples of the spatial decomposition that assumes preliminary subdivision of the space occupied by the scene objects (Jimenez et al. 2001, Klosowski et al. 1998). As a result, spatial localisation of objects and search of nearby objects in the scene can be significantly improved allowing various time consuming applications like view volume clipping or occlusion culling. Unfortunately, spatial decomposition cannot be directly applied for dynamic scenes appearing in 4D modelling and planning applications. Because of temporal changes, statically deployed spatial structures have to be permanently updated while the objects are replaced, appear or are removed in the scene space.

In this paper we discuss an approach to 4D modelling through spatio-temporal decomposition allowing effective access to large project data relevant to a given focus time and analysed space domains. Three partitioning schemas exploiting peculiarities of spatial and temporal coherence of pseudo-dynamic scenes are presented and estimated against typical requests and performance requirements.

Previously there were attempts undertaken to partition hierarchically both the time and space domains. Data structures like Finkelstein's tree (Finkelstein et al. 1996), space-partitioning time tree (Zhiyan & Chiang 2009), Shen's tree (Shen et al. 1999) have been proposed and investigated mainly in the context of fast volume rendering and generating multi-resolution videos. Adaptive and irregular octrees provide interesting examples of dynamic partitioning strategies allowing for real-time modifications of a scene while retaining many of the benefits of static spatial schemas (Shagam & Pfeiffer 2003, Sudarsky & Gotsman 1999, Whang et al. 1995).

The mentioned ideas and principles of spatio-temporal decomposition have been widely utilised in computer graphics methods intended, in particular, for collision detection in dynamic scenes. Our contribution is an adoption of these principles to problems of 4D modelling and planning of large projects as well as comparative complexity analysis of three partitioning schemas looking promising for the discussed purposes.

The rest of the paper is organized as follows. Section 2 describes peculiarities of pseudo-dynamic scenes appearing in the considered applications for 4D project modelling and planning. In section 3 we present three schemas for spatio-temporal decomposition of project data and point out the differences from known results obtained mainly in computer graphics. In Section 4 theoretical estimates of complexity for all the schemas are derived in conformity to typical visualization scenarios and requests. Section 5 provides a comparative analysis and recommendations on practical use of the presented schemas. In conclusions the final results obtained are summarized.

2 PROBLEM STATEMENT

Performance is a crucial factor for 4D modelling and planning applications targeted at the scheduling of large industrial projects. Visualization of complex dynamic scenes as well as identification and resolution of spatio-temporal clashes may require significant CPU resources. These problems are common for many geometric reasoning applications like CAD/CAM, robotics and automation, computer graphics, and virtual reality. But the considered applications have their own peculiarities having a strong impact on performance optimisation through spatio-temporal decomposition. We consider that the scenes originating from 4D modelling and planning applications have the following characteristics:

High complexity: The scenes may consist of thousands and millions of objects with their own 3D model representations and dynamic behaviours. The objects can be both relatively simple shapes and assemblies with sub-assemblies, in the result of which the complexity of individual objects and scenes can be essentially varied.
Mixed geometry: The objects may be canonical geometry primitives, algebraic implicit and parametric surfaces like quadrics, NURBS and Bezier patches, convex and non-convex polyhedrons, solid bodies given by constructive solid geometry (CSG) or boundary representation (BREP). No matter which geometry models are used for the scene specification.
Pseudo-dynamic motion: All the object motions are discrete in time and known in advance (in contrast to real-time simulation in virtual reality environments or motion planning applications). Due to high complexity, detailed specification and analysis of all continuous motions in real industrial projects look redundant and unrealistic. In the scope of the adopted model both discrete displacement, and instantaneous appearance, and disappearance of objects are allowed.

Let us discuss how spatio-temporary decomposition methods can be applied for 4D modelling of large projects with scenes having the mentioned characteristics. First we define underlying data structures utilized by the presented partitioning schemas and then introduce the basic concepts of the scene model applied for deriving theoretical estimates of complexity for typical model requests.

The utilized time tree is a self-balancing binary search tree. It provides an effective data structure for mutable ordered sequence of time points. The root of the time tree corresponds to the entire time domain over which a dynamic scene is analyzed. The time domain is recursively partitioned into intervals for the subtrees by time points until the intervals become single points in the tree leaves. Without regard to particular AVL, red-black or AA structures the binary search trees allow the lookup, insertion, and deletion operations in logarithmic time and tree traversal—in linear time on the number of points.

The applied regular octree is a spatial data structure that successively partitions a space domain into 8 equally sized cells. Starting from a root, cells are successively subdivided into smaller cells under certain conditions, namely, when a cell contains more than a specified number of objects and it contains at least one object occupying the relative volume less than the given threshold. Compared to methods that do not partition space, octrees can improve execution times for querying and processing data. Typical basic operations over octrees are point location, region location, and neighbour searches that have logarithmic complexity on the number of cells.

Both time tree and octree structures are well suited for solving various computational problems like collision detection and view volume clipping. In different ways they exploit the same evident principle: one needs to analyze only those events and related objects that are in feasible domains of the space and time partitions.

Although 4D modelling and planning applications provide for specific functionalities, most of them employ common requests connected with retrieval of data relevant to given time and space domains. Such requests are especially important for advanced 4D systems targeted on large-scale projects and avoiding allocation of whole project data in computer RAM. Instead, the data are dynamically loaded as they become feasible for the performed functions and are released as soon as they are unnecessary.

In this paper four types of requests are considered:

– deployment of auxiliary structures for fast retrieving and accessing project data (Q1);
– reconstruction of the whole scene (or feasible fragments) by given focus time (Q2);
– volume clipping of the scene by given view camera frustum (Q3);
– animation of the project progress using a moving camera (Q4).

It is suggested that the first request Q1 is executed before 4D modelling session. Once being deployed, auxiliary structures can be reused to execute subsequent repeated requests in a more effective way.

The scene reconstruction and volume clipping requests assume incremental updating of the scene or its feasible fragments. It is suggested that the scene representation has been already determined for current time and fixed camera position and it is required to update it taking into account the changed focus time and the moved camera position.

The scene reconstruction request Q2 corresponds to the first option and can be interpreted by looking at the presented screenshot of Synchro system (see the Figure 1). The graphical user interface of the Synchro combines and coordinates both Gantt chart traditional for most project management applications and 3D views typical for CAD systems. By shifting the focus time line at the Gantt chart, the user can observe the project progress in 3D views. View camera positions are preliminary chosen by the user so that most interesting and critical issues of the project plan can be thoroughly investigated. There is no need to update and to visualise the whole scene representation for this purpose. Only objects located in view camera frustum should be requested, involved in the scene and then be visualised.

The volume clipping request Q3 corresponds to the second option and can be illustrated by the same figure. Focus time line remains fixed at the Gantt chart as camera position in one of the 3D views is changed. This type request is usually invoked when the user tries to investigate the model snapshot by applying zooming, translating and rotating operations over the scene. It can be done explicitly or implicitly in the scope of well-known navigation paradigms like 'walk', 'examine', 'bird's eye'.

The animation request Q4 reproduces another meaningful use case. For example, the Synchro system provides for advanced tools for preparing animations of 4D project plans. During the animation the camera can be smoothly moved so that the observer can see the project plan issues in time sequence from most convenient perspectives.

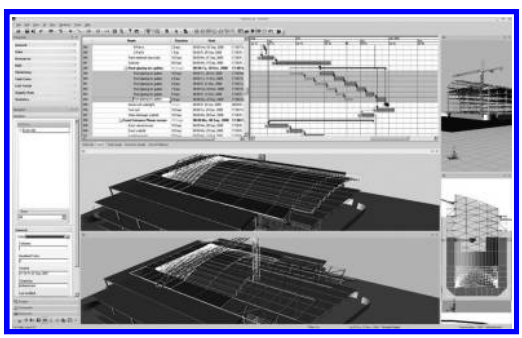

Figure 1. The screenshot of the Synchro system.

Thus, the request Q2 implies the retrieval of project data relevant to varied focus time and fixed space domain, the request Q3—to the varied space domain and fixed focus time and, finally, the request Q4—to simultaneously varied focus time and space domain. The request Q1 is related to the preliminary deployment of auxiliary data structures needed for further effective retrieval and access.

3 PARTITION SCHEMAS

Pseudo-dynamic, event-driven model has been adopted by the most of 4D applications. It assumes that all the scene changes occur in fixed points of time and space domains and are caused by predetermined events or activities.

Such model is quite natural for project management methodology. Activities and Work Breakdown Structures (WBS) can be directly associated with some elements of the 3D scene and profiles like 'installation', 'removing', 'displacement', 'maintenance'. Then the project plan can be visually interpreted and modelled by showing, removing or moving corresponding elements of the scene in fixed time and space points. Each activity or WBS is assumed to give rise to a pair of events occurred in its start and finish time points.

The Figure 2 illustrates how a project plan represented at the Gantt chart can be interpreted within the discussed pseudo-dynamic, event-driven model. A project activity 'Activity2' starts and finishes at 'Time1' and 'Time2' points marked by ticks at the calendar axis. The 3D element 'Element' has been assigned to the activity with the defined profile 'Maintenance'. This profile realizes the behaviour similar to temporary installation of equipment or to temporary displacement of materials at the project site. The profile is emulated by a pair of events corresponding to appearance of the 3D element at the activity start point and its disappearance at the finish point. The element is shown in the scene position 'Loc' while the activity is performed.

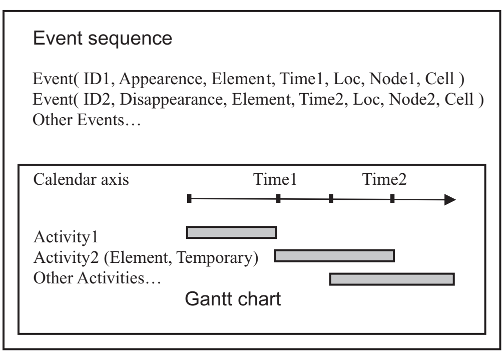

Figure 2. The representation of scene events via Gantt chart.

In the consideration below the events are represented by seven-tuple structure {ID, TYPE, ELM, TIME, LOC, NODE, CELL}, where ID—event identifier, TYPE—event type (that takes one of the values 'Appearance', 'Disappearance', or 'Displacement'), ELM—reference on the associated 3D element, TIME—event time, and LOC—spatial location of the element in the scene (usually defined by transformation matrices).

If time tree and octree have been computed and deployed, then the event structure can be extended by corresponding references NODE and CELL identifying the time tree node and the octree cell associated with the event. Thereby, spatio-temporal localisation of events can be immediately carried out using the auxiliary tree structures and then can be applied for efficient request processing. Nevertheless, there may be different partitioning schemas utilising similar tree structures. Three dynamic partitioning schemas are discussed below.

3.1 *Dynamic spatio-temporal partitioning schema*

The first presented DST schema combines a time tree deployed for whole project and an isolated dynamic octree whose representation is permanently updated to correspond to a given focus time of the project.

The time tree is computed once using all the time points of events appeared during the modelled period. Time tree nodes are interrelated with corresponding event tuples by unidirectional associations. Thereby, events active in a given time interval can be effectively retrieved using the time tree lookup.

The octree cells contain lists of 3D elements which are present in the scene for a given focus time and are placed in the corresponding tree cells. Spatial localisation of 3D elements can be done through sequential search of the octants of minimal size surrounding the elements or their axis aligned bounding boxes (AABB). In this paper we assume that the elements are placed in the octants having approximately the same size. But if a localised element or its AABB intersects underlying planes of high level octants, then the element is replicated in adjacent octants and the process is continued at lower levels until a cell contains more than a specified number of elements and at least one element takes the relative volume less than the given threshold.

The dynamic octree is updated or recomputed every time when a project focus time is changed.

Therefore, its structure and content may undergo to significant changes during 4D modelling session. Nevertheless, the element lists contained by the octree cells correspond to complete representation of the whole scene for any fixed focus time. The Figure 3 illustrates how octree cells, time tree nodes, 3D elements and event tuples are interrelated each other.

3.2 *Extended spatio-temporal partitioning schema*

The Entended Spatio-Temporal (EST) partitioning schema can be considered as an extension of the DST schema. It looks very similar to DST due to both the time tree and octree are deployed as primary structures (see the Figure 4). But it has principal distinctions.

The first distinction is that octree cells contain reference lists for events appeared in the corresponding octants (more exactly, multiple associations with event tuples). These additional references can be computed in the beginning of the modelling session and then be reused for localisation of scene elements. As both the time tree and the octree are deployed once, the EST schema should be considered as static. Contrary to the DST schema assuming permanent changes of the octree structure and content during modelling sessions, the octree structure and event lists are computed once. Nevertheless, more detailed analysis shows that dynamic lists of 3D elements should be remained in each cell to be capable to incrementally reconstruct the scene for any given focus time. In this respect both DST and EST schemas share common organisation principles.

The second distinction is connected with the way how the element lists are formed and updated. Contrary to the DST schema assuming that the cell lists relate to a common focus time point, element lists in the EST schema may relate to different time points. Thereby, even being consolidated, the element lists may not reproduce the scene representation correctly.

Indeed, there is no need to reconstruct the whole scene for a fixed focus time and to update it every time when the focus is changed. Instead, only the visible cells should be processed and the element lists are updated. Therefore, each octree cell stores own time point for which its element list has been formed. If the cell space becomes visible and its content is to be investigated, then the element list is updated taking into account all the events appeared between last and recent focus times.

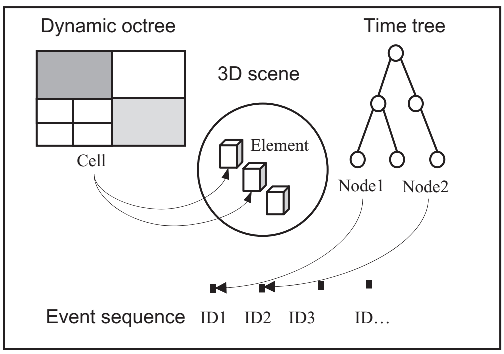

Figure 3. The DST partitioning schema.

3.3 *Advanced spatio-temporal partitioning schema*

Finally, we present Advanced Spatio-Temporal (AST) partitioning schema that can be considered as a further evolution of the DST and EST schemas. Its main distinction is that the AST schema first partitions the space domain by an octree and then for each octree cell partitions the time domain by a time tree (see the Figure 5). By the construction

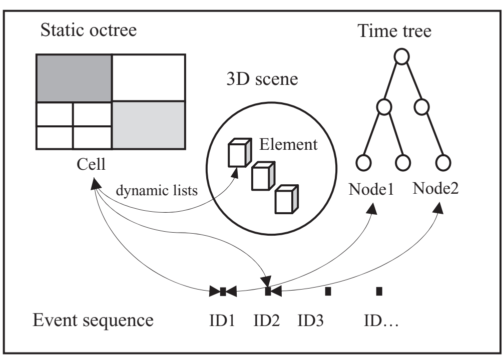

Figure 4. The EST partitioning schema.

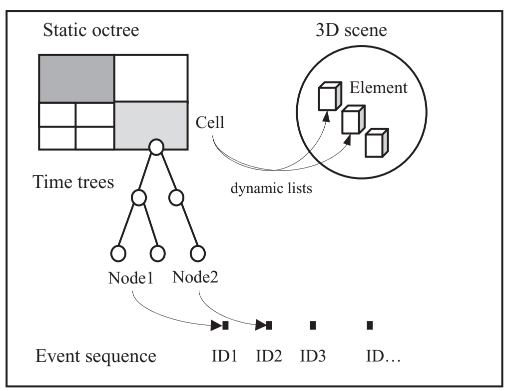

Figure 5. The AST partitioning schema.

it is very similar to Shen's tree. The key difference of the proposed schema and its principal advantage is that nodes of deployed time trees are associated with scene events rather than scene objects. Because of the events identify changes in the scene, the AST partitioning schema avoids the replication of identical elements peculiar to Shen's tree.

As opposite to the DST and EST schemas, the AST assumes that the octree is primary and time trees are secondary. Therefore, only time tree nodes in the AST are associated with events. The AST schema remains lists of 3D elements similar to the EST schema. It is deployed once in the beginning of the modelling session, but the element lists are formed and updated dynamically depending on parameters of the last spatio-temporal request. It is very suitable for the requests combining parameters of both time and space domains, but useless for time requests because of the necessity to lookup whole spatial structures to collect the events appeared in a given time interval. This capability has been lost in comparison with the EST schema whose time tree nodes contain direct references on the associated event tuples.

4 PERFORMANCE ANALYSIS

To derive practically meaningful estimates of performance, let a dynamic scene is represented by identical elements and by similar appearance events so that each event adds a new element in the scene and the final number of elements equals to N. It is suggested that the elements are uniformly distributed over the scene space and the events are equiprobable during the whole modelled time period.

Volume factor $\nu = (\Delta x \cdot \Delta y \cdot \Delta z)/(x \cdot y \cdot z)$ expresses relative volume occupied by every element (more exactly, AABB surrounding the element) with respect to overall scene dimensions x, y, z. Linear factor $\delta = \max(\Delta x/x, \Delta y/y, \Delta z/z)$ expresses maximum relative size of the bounding box. Under the additional assumption about the scene and elements proportions $\Delta x/x = \Delta y/y = \Delta z/z = \delta$, the volume factor takes the value $\nu = \delta^3$.

Let us define auxiliary parameters α, β, γ characterizing the 4D modelling session. The parameter $\alpha > 0$ defines relative volume density of the scene for a final time point as $\alpha = \nu$ N. The volume of view frustum with respect to the whole scene space is given by the relative parameter $\beta \in [0, 1]$. And the relation $\Delta t/t$ of the analyzed time interval Δt to whole modelling period t is defined by the parameter $\gamma \in [0, 1]$.

All the performance estimates are derived for the average case under the assumptions about the scene model peculiarities. Let C_{Time} is the average cost of point classification in time tree nodes, C_{Box} is the average cost of spatial localisation of the given AABB in octree cells (relatively underlying subdivision planes of each higher level octant). In similar way, C_{Cone} is the cost of testing whether the given AABB is located inside view frustum (admitting intersections with its planes) or exactly outside it. For simplicity, costs for navigating over the trees, costs for gathering of elements and events as separate collections are taken negligible and eliminated from the performance analysis. Costs for forming and rendering of 3D scenes are not related to the partitioning schemas and are beyond of the consideration too.

4.1 *Deployment request Q1*

First of all, let us estimate deployment costs for the presented partitioning schemas. Costs for octree deployment can be obtained independently from the time tree costs for all the schemas. Octree deployment costs are presented only for the EST, AST schemas. These costs are missing for the DST schema as the octree structure and its content are permanently updated during the 4D modelling session. According to the accepted scenario, at a start time it does contain neither elements nor cells and, therefore, does not require any computations. At a finish time, it contains all the scene elements placed in the deployed octant cells. Such costs are related to other request types.

Under the scene model assumptions, identical elements are localized in the leaf octants at the level $L = \log(1/\delta)$ if $\alpha \geq 1$ and $L(N) = 1/3 \log(N)$ in the opposite case $\alpha < 1$. Here L is a height of the octree. The probability of simultaneous intersection of localized element and three underlying planes of octant of level $l \in [1, L]$ equals to δ_l^3, where $\delta_l = 2^l \delta$ is an effective relative size of the element AABB. By the octree construction, it causes the element replication and placement in eight children octants of the level l + 1. In similar way, the probability of intersection of two planes and replication of the element in four octants is equal to $3\delta_l^2 (1 - \delta_l)$. The probability of intersection of one plane and replication of the element in two octants counts $3\delta_l (1 - \delta_l)$. And finally, the probability of the element localisation exactly in one octant is $(1 - \delta_l)^3$.

Thereby, the average distribution of the element number at the level l is given by the formula:

$$R_l = 8\,\delta_l^3 + 12\,\delta_l^2 (1 - \delta_l) + 6\,\delta_l (1 - \delta_l) + (1 - \delta_l)^3$$

The average cost of element localisation in the whole octree is given by C_{Box} R(L), where a summarizing function R(L) is defined as $\Sigma_{l=1}^{L} 1 \cdot R_l$.

Then, the total costs for the octree deployment take the value C_{Box} R(L)N as each appearance event requires exactly one localisation operation for the corresponding element. It can be shown that the function R(L) is expressed by the formula:

$$R(L) = (1/98)*(5\ \delta^3 2^{3L+4} - 35\ \delta^3 2^{3L+4} L - 80\ \delta^3 - 49\ \delta^2 2^{2L+3} + 147\ \delta^2 2^{2L+3} L + 392\ \delta^2 - 147\ \delta 2^{L+2} + 147\ \delta 2^{L+2} L + 588\ \delta + 49\ L^2 + 49\ L)$$

with upper limit given by $R(L) \leq 4*(L+1)L$.

The time trees are static structures in all the presented schemas and the deployment costs can be directly calculated. The binary search trees in the DST and EST schemas contain exactly N nodes and their computing can be done in C_{Time} log(N!). In the AST schema time trees are formed in each of 8^L leaf octants with the average number of events equal to $N/8^L$. Therefore, total costs to deploy all such trees within the AST schema count $C_{Time}\ 8^L \log((N/8^L)!)$.

By concluding, the deployment costs for DST, EST and AST schemas are expressed by the corresponding formulae:

$$C1_{DST} = C_{Time} \log(N!)$$
$$C1_{EST} = C_{Time} \log(N!) + C_{Box} R(L)N$$
$$C1_{AST} = C_{Time}\ 8^L \log((N/8^L)!) + C_{Box} R(L)N$$

4.2 *Scene reconstruction request Q2*

The scene reconstruction request Q2 is executed under the suggestion that the scene is known for the previous focus time and it is required to update the scene for the recent focus time. All the events appeared during this interval must be collected and the corresponding updates must be done in the scene.

The request results for the EST schema can be obtained in two ways. Starting with the time tree, feasible events appeared in the analysed time interval can be determined in $C_T\ \gamma N$. The relative factor γ defines here the time duration over which the scene is reconstructed. The value $\gamma = 0$ corresponds to the confluent case when no events appear and there is no need to update the scene. The value $\gamma = 1$ corresponds to reconstruction of the scene over the whole modelling period. Additional checks whether the detected events appear in the view frustum take $C_{Cone}\gamma N$.

The second way assumes the primary use of the octree. Navigation through visible octants and checks against appearance of the associated events in the given time interval require $C_{Time}\beta R(L)N$. The factor R(L) takes into account the expected number of elements at the octree level L that differs from the original number due to the element replication.

Applying the optimal strategy combining both methods, the cost function takes the form:

$$C2_{EST} = \min((C_{Time} + C_{Cone})\gamma N,\ C_{Time}\beta R(L)N)$$

The performance estimate for the AST schema can be derived in a similar way, but the lookup process should be expanded on partial time trees deployed in the octree leaves. Each such tree provides for fast binary search of those events which appear during the given time interval in the parent octant. Gathering actual events through all visible octants and feasible nodes, the resulting collection can be obtained and processed to update the scene. Taking into account the uniform distribution of elements over the scene space and events over the modelled time period, the expected number of events appeared in the view frustum during the time interval is given by the value $\beta\gamma R(L)N$. Therefore the total costs are expressed by the corresponding formula:

$$C2_{AST} = C_{Time}\ \beta\gamma R(L)N$$

Finally, the request Q2 can be satisfied using the DST schema. By iterating through the time tree nodes, actual events can be identified in $C_{Time}\ \gamma N$. The octree is dynamically recomputed if the focus time has been changed. For each detected appearance event the associated element should be placed into the corresponding octant according to the accepted modelling scenario. To update the octree γN elements must be placed. As explained above, it can be done in $C_{Box}\ R(L')\ \gamma N$. Therefore, the final performance estimate for the DST schema takes a form:

$$C2_{DST} = C_{Time}\ \gamma N + C_{Box}\ R(L')\ \gamma N$$

Here the height of the dynamic octree $1 \leq L' \leq L$ depends on the number of already placed elements as $L' = \log(1/\delta)$ if $\alpha\,\gamma \geq 1$, and $L'(N) = 1/3 \log(\gamma\ N)$ in the opposite case $\alpha\,\gamma < 1$.

4.3 *Volume clipping request Q3*

The volume clipping request can be executed in a way common for all the presented schemas. Again, iterating through the octree the visible octants located in the view frustum are determined and associated events (or elements) are collected. Let a camera is moved so that each new view frustum takes additional scene space volume with the relative factor $\beta \in [0, 1]$ introduced above. To determine which octants are visible, it is necessary to iterate approximately over $\beta\ \Sigma_{l=1}^{L}\ 8^l$ cells from the root down to leaves and to check whether they belong to the view frustum or not. By expressing the sum of the geometrical series the computational cost of the volume clipping operation takes a form C_{Cone} $\beta(8^{L+1}-1)/7$. The level parameter corresponds to the octree height fixed for the EST and AST schemas and varied for the DST schema depending on the factual number of processed events and placed elements. The determination of visible octants is a key performance issue for the DST schema, so the following formula takes place:

$$C3_{DST} = C_{Cone}\ \beta(8^{L'+1}-1)/7$$

The EST and AST schemas require additional updates of the dynamic element lists. Remind that although these schemas assume static deployment, the element lists have to be modified to conform to particular time points. It avoids unnecessary updates of the element lists belonging to the invisible octants and simplifies the scene reconstruction for the octants which become visible. Therefore, to execute the volume clipping request the reconstruction operation must be invocated for those cells which become visible and whose lists do not conform to the recent focus time. The cost estimates for the reconstruction operation have been obtained in the previous section. Thereby, the total costs for the volume clipping request are expressed by the following similar formulae:

$$C3_{EST} = C_{Cone}\ \beta(8^{L+1}-1)/7 + C_{Time}\ \beta R(L)N$$

$$C3_{AST} = C_{Cone}\ \beta(8^{L+1}-1)/7 + C_{Time}\ \beta\gamma R(L)N$$

The formulae have been derived under the suggestion that the scene reconstruction request is executed first time for the octants belonging to the changed view frustum.

4.4 *Animation request Q4*

The animation request assumes simultaneous changes of both the focus time and the view camera position. Therefore it can be represented by a pair of the scene reconstruction and volume clipping operations. As a result, its cost can be estimated as a simple sum of the auxiliary request costs. It is true for the DST schema:

$$C4_{DST} = C2_{DST} + C3_{DST}$$

For the EST and AST schemas more adequate dependencies can be identified as the volume clipping operations provide for the partial scene reconstruction. Thus, the following cost relations can be established:

$$C4_{EST} = C3_{EST}$$
$$C4_{AST} = C3_{AST}$$

5 COMPARATIVE ANALYSIS

Let us compare the three presented partitioning schemas with regards to typical requests and common performance requirements imposed upon their execution. The comparative analysis of the computational costs enables to formulate recommendations on the effective use of the schemas for large project data. The complexity formulae obtained for all the introduced requests and the specified schemas are summarised in the Table 1.

First of all, it can be concluded that the costs for deployment of auxiliary structures may be varied significantly. The asymphtotic estimates of the complexity O(NlogN) coincide each other for the time tree deployment, although the AST schema looks more preferable for practical purposes. The octree deployment for the EST and AST schemas takes the same costs $O(N\log^2 N)$ which are fully avoided by the DST schema.

The scene reconstruction can be efficiently done in $O(N\log^2 N)$ for the requests assuming significant fragmentation of time and space domains using the AST schema. Other schemas have the same asymphtotic estimate with multipliers larger than the factor $4/9C_{Time}\beta\gamma$ admitted by the AST schema.

The DST schema is most efficient for the volume clipping requests as it operates mainly with the partially deployed octree and avoids additional costs for the scene reconstruction in latent octants. The AST looks more preferable than the EST as it simplifies the checks for active events using multiple time trees deployed in the octree leaves. If the time interval for the reconstruction is relatively small for latent octants, then it provides for performance advantage over the EST schema.

Finally, the AST and EST schemas are well suited for the animation requests. The complexities are the same as those of derived for the volume clipping operation. The DST schema requires for total updates of the octree structure which

Table 1. The complexity costs for the partitioning schemas.

Q1	$C1_{DST} = C_{Time} \log(N!)$
	$C1_{EST} = C_{Time} \log(N!) + C_{Box}\ R(L)N$
	$C1_{AST} = C_{Time}\ 8^L \log((N/8^L)!) + C_{Box}\ R(L)N$
Q2	$C2_{DST} = C_{Time}\ \gamma N + C_{Box}\ R(L')\ \gamma N$
	$C2_{EST} = \min((C_{Time} + C_{Cone})\gamma N, C_{Time}\ \beta R(L)N)$
	$C2_{AST} = C_{Time}\ \beta\gamma R(L)N$
Q3	$C3_{DST} = C_{Cone}\ \beta(8^{L(+1}-1)/7$
	$C3_{EST} = C_{Cone}\ \beta(8^{L+1}-1)/7 + C_{Time}\ \beta R(L)N$
	$C3_{AST} = C_{Cone}\ \beta(8^{L+1}-1)/7 + C_{Time}\ \beta\gamma R(L)N$
Q4	$C4_{DST} = C2_{DST} + C3_{DST}$
	$C4_{EST} = C3_{EST}$
	$C4_{AST} = C3_{AST}$

are unnecessary for other considered schemas. Each of the presented schemas has own benefits and drawbacks compared with the other solutions. The criterion of uniformly high performance for different type requests seems to be adopted for the choice of optimal schema.

6 CONCLUSIONS

Thus, the spatio-temporal decomposition approach to 4D modelling of large-scale industrial projects has been presented. The approach assumes special data structures and facilities to effectively execute typical requests relevant to given time and space domains. Three partitioning schemas have been presented and analysed to satisfy performance requirements. The schemas exploit coherence peculiarities of the pseudo-dynamic, event-driven scenes appearing in 4D modelling and planning applications. The derived theoretical estimates of the complexity as well as the conducted computational experiments prove benefits of the schemas and their wide potential use.

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Developing a BIM-oriented data model to enable sustainable construction in practice

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ABSTRACT: Sustainable construction is an emerging field of science that aims at incorporating the general sustainable development concepts into conventional construction practices. In spite of its importance and the proliferation of literature on sustainable construction, it is not yet a standard industry practice. This paper recognizes some key barriers to the implementation of sustainable construction, and discusses a new research effort undertaken by the authors that aims to eliminate some of the barriers and help in enabling sustainable construction. The methodology adopted exploits the power of systems engineering and the rapid evolution of Building Information Modelling (BIM), pursuing the development of a BIM-oriented data model for enabling sustainable construction. The environment, the built facility, and the construction/production system are abstracted as three interacting Systems of Systems (SoS). Accordingly, the framework for data model development is outlined, illustrating different operating mechanisms.

1 INTRODUCTION

Sustainable construction could be defined technically as "a holistic process in which the principles of sustainable development are applied to the comprehensive construction cycle, from the extraction and beneficiation of raw materials, through the planning, design, and construction of buildings and infrastructure, until their possible final deconstruction, and management of the resultant waste (Du Plessis 2002). The construction industry has been trying to adopt sustainable construction practices as early as the late 1980s. Still, after more than 20 years of attempts, sustainable construction is not yet a standard industry practice. As an absolute value, the number of buildings incorporating sustainability features is continuously increasing. However, this value strongly fades out when compared to the number of newly delivered developments in most countries of the world. That figure was less than 1% in the United States as of 2008 (Williams & Dair 2006, and Keeler & Burke 2009).

A number of published research work identifies a long list of technical and non-technical barriers to sustainable construction implementation as a standard practice of the industry, including Landman (1999), Blair & Evans (2004), Matar et al. (2004 & 2008), and Williams & Dair (2006). Amongst the barriers identified are (1) the higher initial cost of sustainable buildings, (2) the slow rate of return on investment on that higher initial cost, (3) the lack of interest from major industry stakeholders, (4) the ambiguity of sustainable construction practices to the wide base of industry practitioners, especially when contrasted to the clear defined codes and standards available for most of the common construction disciplines and activities, (5) the lack of sufficient education and training among industry practitioners, etc.

This paper recognizes specific technical barriers related to the wide-base current operational structure of the construction industry. As shown in coming sections of the paper, these specific barriers are related and can be overcome by the deployment of a common and interoperable model for representing the interaction between construction industry—in terms of both: products and processes—and the environment. These barriers are (1) the current characteristic fragmentation of construction industry entities, (2) the weak and slow adoption of Information and Communication Technology (ICT) tools by the construction industry, and (3) the clatter, confusion and inefficiencies of current tools and approaches to sustainable construction.

This paper utilizes a systems approach to model (1) the built facility, (2) its production system and processes, and (3) the natural environment as three interacting "systems of systems". Furthermore, the paper outlines the foundation for a research effort initiated by the authors to develop a data model that exploits ICT to enable sustainable construction, capitalizing on Building Information

Modelling (BIM) as a new technology that is rapidly adopted by many construction industry stakeholders.

The paper consists of five sections starting by a brief introduction that highlights both the research background and objectives. The barriers to sustainable construction addressed by the model are then explained. Next to that, the architecture of the proposed model is outlined, discussing the use of Building Information Modelling (BIM) and Industry Foundation Classes (IFCs). The last section discusses research conclusions and future work.

2 BARRIERS TO SUSTAINABLE CONSTRUCTION

As mentioned earlier, a number of published research work identified a long list of technical and non-technical barriers to sustainable construction. This paper, however, recognizes a number of structural and technical barriers that are inherent to the common business model in the construction industry, and negatively impact the implementation of sustainable construction practices. These include (1) the current characteristic fragmentation of construction industry entities, (2) the weak and slow adoption of Information and Communication Technology (ICT) tools by the construction industry, and (3) the clatter, confusion and inefficiencies of current tools and approaches to sustainable construction. The following sections provide further explanation.

2.1 *Characteristic fragmentation of construction industry entities*

The most common practice in the construction industry involves moving from one project step/activity to another in a sequential manner. Based on a client brief, the architect produces an architectural design, which is given to the structural engineer, who on completing the structural design passes the project to the quantity surveyor to produce the costing and bill of quantities, and so on. This goes on until the project is then passed on to the contractor who takes responsibility for the construction of the facility (Khalfan et al. 2007). This fragmentation leads to misperceptions and misunderstandings, a high rate of omissions, errors and design changes, and makes deploying a new concept and its necessary practices—like sustainable construction—something difficult and costly. Accordingly, leading entities and researchers on sustainable construction stress on the necessity of an integrated project approach to achieve sustainability (Matar 2007, Krygiel & Nies 2008, and Keeler & Burke 2009).

However, with 65% of construction firms con sisting of less than 5 people (Eastman et al. 2008) and operating as entrepreneurial small business entities, that required integration is very difficult to realize. For instance, the fact of the matter is that maintaining one-to-one communication and exchange of information between a number of project executing entities requires having a number of communication channels $C = (n^2 – n)/2$, where n is the number of project executing entities. For instance, in cases of 6, 7, or 8 entities, which are the minimum typical in an average project, 15, 21, or 28 communication channels are required respectively. As clear from the formula, the number of channels is directly proportional to the number of entities in a second degree proportionality. This multiplication of communication channels eventually decreases communication efficiency, increases the possibilities for errors and omissions, and ultimately leads to weakened or incorrect implementation of the principles communicated through these channels.

2.2 *Weak and slow adoption of Information and Communication Technology (ICT)*

Already one decade has passed of the 21st century, and a wide range of businesses are currently enjoying the extreme advantages of using Information Technology (IT) and Information Systems (IS). Information technology involves only the hardware and software components of computing systems. Information systems extend the scope to include synergistically operating components of hardware, software, data, processes, and people, in a fully integrated system whose main objectives are to fully exploit and develop organizational and business knowledge to realize maximum benefits regardless of the line of business or the type of industry (Motiwalla & Thompson 2009).

Unfortunately, that is not the case for the construction industry. The rate of adoption of basic Information and Communication Technology (ICT) is notoriously low—let alone fully integrated information systems (Andrews et al. 2006). Amongst the most cited reasons for this are: (1) being a labor intensive industry in comparison with other industries that are either fully automated or white-collar industries, (2) being fragmented by nature, and (3) being composed mainly of budget constrained small businesses that are usually unable to invest in ICT.

Furthermore, the current base of ICT tools available for the construction industry suffers several drawbacks including that: (1) the existing software packages are often single entity oriented, meaning that they are designed to support the specific activities of a single building trade and do not really support architecture/engineering/construction (AEC) activities in their cooperative dimensions (Kubicki et al. 2009). (2) Plus, these tools suffer a strong lack of interoperability. For instance, both CAD and project scheduling software use and generate information related to geometry, quantities, cost budgets, construction schedules, etc. However, most common planning and scheduling software cannot process basic alphanumeric information stored and derived from CAD software, such as quantities and material types (Eastman et al. 2008).

Strong evidences indicate that the proper use of ICT in construction can significantly facilitate the deployment and realization of sustainable construction through enabling integrated data exchange, information access, intelligent document and knowledge management, and application interoperability (Ugwu 2005, Andrews et al. 2006).

2.3 *Inefficiencies of current tools and approaches to sustainable construction*

In its attempt to realize sustainable construction, the construction industry has generated and developed a large number of tools and a dramatic quantity of recommendations and vaguely defined practices including: (1) general references for sustainable construction, (2) models and frameworks, (3) guidelines and heuristics, (4) assessment and evaluation tools, and (5) research guides (Pearce & Vanegas 2002). Despite this proliferation of literature, there is still no general consensus on how comprehensively and uniformly define the concept of sustainability as it pertains to the built environment, nor is there consensus on what aspects of the built environment should be considered in evaluating the sustainability of a built facility (Pearce & Vanegas 2002). The result of all this is clutter and confusion, with a proliferation of eco-methods, eco-labels, and eco-guidelines (Trusty 2004).

A recent study included a survey carried out on behalf of the US General Services Administration (GSA), which counted more than 150 building performance and sustainability evaluation tools for the purpose of selecting a mostly reliable and comprehensive tool for the US GSA sustainable construction/procurement needs. At the first screening, only 34 of these tools qualified as sufficiently comprehensive building evaluation tools covering multiple sustainability criteria, adopting a 'whole building' approach and covering more than one life cycle phase. At the second screening stage, only five sustainable building rating systems scored positively on all of the screening criteria. These were the BREEAM, CASBEE, GBTool, Green Globes US and LEED (Fowler & Rauch 2006).

Not only this, but the US National Institute of Standards and Technology (NIST) conducted research to evaluate LEED using meticulous Life Cycle Analysis (LCA) principles in order to assess its robustness and validity as a correct sustainability assessment tool for the built environment. The research identified discrepancies in the calculation method leading to disparities and inconsistencies of calculated outcomes. These discrepancies undermine the achievement of individual LEED credit intentions and the goals of the LEED program as a whole. The research also questioned the appropriateness of set thresholds and feared that LEED strongly favors common market practices in a manner that trivializes harmful effects on the environment. In addition to that, the research proved that two incomparable projects with different environmental impacts could realize the same LEED rating, and hence creating an illusion that they have similar environmental footprint—in contradiction to the truth of the matter (Scheuer & Keoleian 2002). Furthermore, another study evaluated the energy performance of 21 LEED certified buildings after their construction and concluded that the number of LEED energy efficiency points did not correlate with actual energy savings (Diamond et al. 2006).

Finally, most of these sustainability assessment tools were developed and have shown adequacy principally addressing the design phase of a building project. There remains a strong need for addressing the construction, operation and maintenance phases of a built facility (Shen 2005, and Chen et al. 2005).

This current status of having a confusing range of definitions, and tools of questionable reliability and scientific bases, leads to hindering the wide adoption of sustainable construction practices and might well lead to doubtful performance results.

3 A SYSTEMS APPROACH TO SUSTAINABLE CONSTRUCTION

At this point, where both the need for sustainable construction and the existence of several barriers to its realization are undeniable, there is a strong need for a well defined approach that adequately addresses critical areas of sustainability in line with the factual current state of the construction industry, its capacities and capabilities, and the different needs of different stakeholders.

This paper utilizes a systems approach as a foundation for a research effort undertaken by the authors to develop an adequate scalable model for realizing sustainable construction, building on the fundamental hypotheses of sustainable development where the development and operation of human and societal systems should be done in a manner that does not jeopardize the total equilibrium of the environmental system.

This model should deliver on and satisfy the following needs:

- The model must adequately represent, but simplify, the breadth of complexities of both the environmental system and the construction product and production systems.
- The model should form the basis for common understanding, and therefore integration between a wide range of stakeholders.
- The model should capitalize on the extreme power and opportunities enabled by Information and Communication Technology (ICT) and information systems in general.
- The model must have robust scientific bases while maintaining ease of use by different industry stakeholders.

3.1 *Systems of systems*

Recently, with the rapid technological advancement and intricacies in the 21st century, there has been a growing interest in a class of complex systems whose constituents are themselves complex (Jamshidi 2009). Typical examples of such *systems of systems* have been proven to exist in aerospace, manufacturing, security, and disaster management disciplines and industries, just to name a few.

A practical definition for a System of Systems (SoS) is that "it is a super-system comprised of other elements that themselves are independent complex operational systems and interact among themselves to achieve a common goal" (Jamshidi 2009). There is an increasing interest in achieving synergy between these independent systems to achieve desired overall system performance or performance objectives.

The key challenges associated with analyzing and engineering a System of Systems include managing interfaces among component systems, the distributed nature of management in an SoS environment, and the challenge associated with adaptive and emergent behavior of the composite systems (Wells & Sage 2009). Traditional systems engineering techniques focused on optimisation for a specific system. Optimizing for an individual system might inflict damage on other systems. However, SoS focuses on optimizing for the whole system of systems, which means optimizing for total and global performance rather than optimizing for any individual system. This is crucial for the case of sustainable development, where the singular optimisation for the benefit of the environmental system could misleadingly prohibit use of resources by human activities, whereas the true objective is to consume resources at a rate that neither overloads the environmental system with production and processing outcomes nor consuming resources at a rate that could be unsustainable by the system.

The following sections incrementally define: (1) the environmental system, (2) the building system (the product), and (3) the construction system (the production system) as three interacting systems of systems. This abstraction and break down as interacting systems shall facilitate the development of the proposed data model for enabling sustainable construction as illustrated in later sections of the paper. Each of these is an *open* system by nature, as a *closed* system has no interaction across its boundaries. According to modern systems theory and laws of physics, these three open systems utilize, exchange, and process only three fundamental types of resources. These are: (1) energy, (2) matter, and in some cases (3) information (Jorgensen et al. 2007). System role missions are executed by system entities, whether physical or logical, to produce value-adding products and possibly non-value-adding co-products, as illustrated in Figure 1.

3.2 *Environmental System of Systems*

A universal characteristic of virtually all systems of systems is that they involve multiple participants with multiple objectives. The Environmental System of Systems, abbreviated hereinafter by (ESoS) is no exception. The ESoS refers to the natural systems that provide, permit, and encourage the formation, the development and the evolution of all other systems of systems on planet Earth (Hipel et al. 2009). The ESoS principally comprises

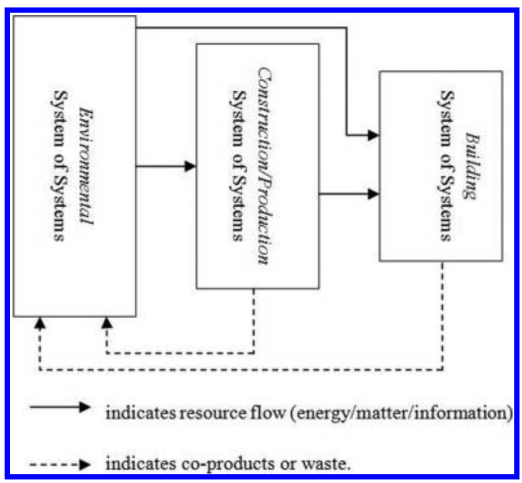

Figure 1. The *Environmental, Construction/Production*, and *Building* Systems of Systems.

four main systems. According to Wasson (2006), Jorgensen (2007) and Hipel et al. (2009), these are:

- The *atmospheric* system environment, representing the gaseous layer that extends from the surface of a planetary body outward to some pre-defined altitude.
- The *lithospheric* system environment, comprising the rigid or outer crust layer of Earth, including continents, mountains, islands, etc; containing most of material resources.
- The *hydrospheric* system environment, consisting of all liquid and solid water systems such as lakes, rivers, rain, underground aquifers, oceans, etc.
- The *biospheric* system environment, defined as the environment comprising all living organisms on Earth, including all environments that are capable of supporting life above, on, and beneath the Earth's surface as well as the oceans. Thus, the biosphere overlaps portions of the atmosphere, hydrosphere, and lithosphere.

It is to be noted that dealing with the ESoS within a specific project context, which is the typical case for a construction project, requires an abstraction of the ESoS to a smaller local environment level encompassing the current location of the project. Figure 2 is a block diagram illustrating the ESoS.

There are some basic principles that govern the behavior of the ESoS (Jorgensen 2007). Of these, the following two principles are fundamental to represent the interaction of the construction industry at both the product and production levels with the ESoS. These two principles are:

1. All ecosystems are *open systems* embedded in an environment from which they receive energy-matter input and discharge energy-matter output.

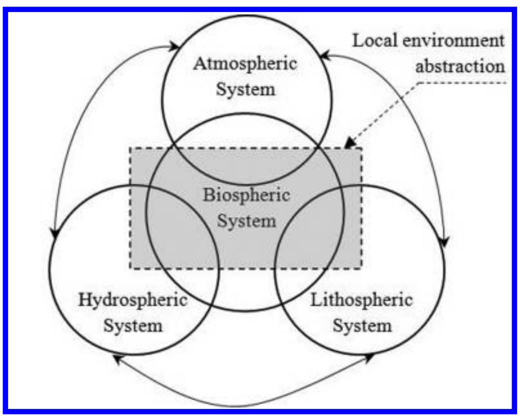

Figure 2. The Environmental System of Systems.

2. *Mass and energy are conserved.* This principle permits writing balance equations to track material and energy flows and conversions, where:

   accumulation = input − output

To illustrate the utility of these principles in modelling for realizing sustainable construction, consider a simple example of a typical structural element such as a reinforced concrete footing. To physically produce the footing, resources including energy and materials are required. The construction/production system procures these resources from the environmental system, and produces the footing through conversion processes that combine these materials and energy producing the footing. The following relations are all valid:

- For any material used, e.g. cement, both the material itself and the required processing energy are exchanged between the ESoS and the production system based on principle (1).
- Any difference between the quantity of materials calculated at design, and that consumed at site is presumably consumed in non-value-adding co-products or waste, based on principle (2). Hence the amount of solid waste generated is calculated.

3.3 *The building as a system of systems*

By simple definition, a building is a general term for manmade structures built to support or shelter human activities such habitation, work, leisure, etc. As a matter of fact, a building could be visualized as a group of independent but interacting systems. Typically, these systems are the architectural, structural, mechanical, and electrical systems. These systems together define the shape, utility, comfort, and environmental performance of a built space.

- The *architectural* system defines the volumes, functions, and aesthetical view of a building. The architectural system is usually the lead system: designed at the very beginning according to an owner's brief and requirements, and sets course and boundaries for other building systems.
- The *structural* system is fundamentally concerned with the support and transfer of all building loads to the ground. The structural system primarily uses different techniques and materials in specific skeletal arrangements to achieve the primary functions of load bearing and load transfer, in addition to helping in providing building shape, and functional objectives of other systems within the building.
- The *mechanical* systems in a building are designed to perform a variety of functions. They are responsible for heating, ventilating, and cooling the indoor environment as well

as supplying freshwater and disposing of wastewater. In addition to these, mechanical systems extend to include fire protection systems.

- *Electrical* systems in buildings are primarily the electrical power supply systems, and data/communications and signal systems. Electrical systems include lighting, alarm systems, distribution systems, acoustic and auxiliary systems.

Although these systems might come into close interaction as in the case of electrical and mechanical systems, and architectural and structural systems, they typically operate independently to support the required human function(s) throughout the life span of the built facility. To produce these systems at the construction/production phase of a built facility life cycle, resources are consumed and co-products are released to the environmental system of systems. During the life span of the built facility, these systems continue to consume resources and produce products and co-products. The efficiency of their operation determines their performance with regard to environmental sustainability.

3.4 *Construction/production system of systems*

The third system of systems involved is the construction/production system. The terminology "construction/production" is intentionally used as the visualization of construction as a production process (Koskela 1992) has proved to be useful and of several applications in lean construction (Lapinski et al. 2006, and Klotz et al. 2007) and construction process reengineering (Mao & Zhang 2008). Any construction project is, in fact, a series of conversion and flow, value-adding and non-value-adding activities that start from project inception and end by operation through the operational life of a facility, and finally by possible deconstruction.

This production system involves a number of interacting subsystems that include, for instance:

- The *business* system necessary for the management and operation of any construction industry organization and its project endeavors.
- The *design management* system responsible for the production of the whole package of design drawings and specifications for the built facility system of systems, including architectural, structural, mechanical, and electrical systems.
- The *project management* system principally responsible for realizing project goals of scope, time, cost, and quality.
- The *construction* system responsible for field production of a built facility system of systems.
- The *facilities management* system responsible for operating and maintaining a built facility with all of its subsystems at maximum efficiency.

Each of these systems operates to deliver its products and goals at six levels of hierarchy. The *organizational, project,* and *activity* levels focus on organizational and project attributes and physical components at a high level, down to project planning and scheduling. On the other hand, the *operation, process,* and *work task* levels focus from the end of high level of operation down to fundamental field action and basic labor and crew-related tasks (Halpin 2006). At each of these levels, different executing entities make countless decision that eventually result in consuming resources and delivering different products and co-products to the ESoS.

4 DATA MODEL DEVELOPMENT

4.1 *Model basis*

The previous section of the paper highlighted the complexity and the breadth of the large number of systems that form together the operational context of the construction industry in general, be it sustainable or not. Sustainability, as an objective, can never be fully realized except when the construction/production system of systems delivers its operations and products—eventually: the built facility system of systems—with sustainability kept in mind.

Considering this number of interacting entities and systems, it is clear that information processing for sustainability could be an extremely challenging task. In practice, the implementation of information processing by most project teams is substantially manual, thus adding to the difficulties facing sustainability implementation. Furthermore, project information in general is produced and processed by different teams independent of one another. Since design is an open-ended problem, i.e. in general there is a large number of design alternatives satisfying the complex needs and provisions; the selection of the optimum design becomes an extremely challenging problem, especially with a set of criteria as new and as complicated as sustainability performance. However, the relatively recent introduction of *Building Information Modelling (BIM)* is rapidly transforming the construction industry, and has the potential to change much of industry practices, and hopefully help in enabling sustainable construction in practice.

4.2 *Building Information Modelling (BIM)*

The glossary of the BIM Handbook (Eastman et al. 2008) defines Building Information Modelling (BIM) as "a verb or adjective phrase to describe tools, processes and technologies that are facilitated by digital, machine-readable documentation about a building, its performance, its planning, its construction, and later its operation." The result of BIM activity is a "building information model." For simplicity, BIM is considered a three-dimensional computer model with its associated databases. (Eastman et al. 2008). What BIM represents is simply a graphical interface for a database of a building project. BIM acts as a central data repository to store and recall different kinds of information about a project. The beauty, strength, and power of BIM come from the fact that the AEC industry has always used and is expected to continue using drawings and visuals as a principal means of communication. Drawing turns into an instinct for the professional engineer/designer. Thus a model based on graphics and visuals is highly communicable for most industry participants, regardless of any underlying complexities or intricacies. This is one main driver for this research endeavor by the authors. If sustainability performance rules and criteria could be directly linked to the most common form of industry communication, then several barriers are already eliminated.

One neutral and potential industry de facto standard for BIM data models and information exchange is the Industry Foundation Classes (IFC) data model. IFC is an object oriented file format with a data model developed by buildingSMART (International Alliance for Interoperability, IAI) to facilitate interoperability in the building industry. The model defines an integrated schema to represent the main physical and logical building objects, including their characteristics and their inter-relationships in the form of a class hierarchy. The IFC hierarchy covers the core project information such as building elements, the geometric and material properties of building product, project costs, schedules and organizations, and even some process related attributes. However, the current IFC is still incapable of providing sufficient information required by the construction management and the sustainable construction domains (Eastman et al. 2008).

4.3 *Model framework and operation*

The framework for development of the proposed data model for enabling sustainable construction in practice departs from a previous research effort carried by the first two authors, which developed a matrix-based quantitative integration framework for attaining sustainable construction. That previous work identified and correlated sustainability parameters to different construction project stakeholders and executing entities during different project life cycle phases, all in one context. A system of metrics developed inherent to the framework facilitated numerical assessment of environmental performance and hence provided means for environmental performance evaluation (Matar et al. 2008). Instead of manually applying the derived metrics, an Environmental Performance Analysis Engine (EPAE) performs computerized assessment of design and production data, either in an iterative manner during design and construction planning phases or in a comparative manner using the IFC-Based project database in case of evaluating production or post-production performance. The EPAE principally comprises (1) rule-based derivation algorithms, and (2) a reference set of environmental performance boundaries derived according to the systems analysis of the environmental system of systems. The rule-based derivation algorithms are developed after the rule-based linking approach developed by Jan Tulke as mentioned by Weise et al. (2009). This rule-based approach identifies and derives the following types of data:

- Master data: representing raw design data, including length, width, height, etc.
- Derivation rules: representing the rules that capture design decisions that were made within processes, for example, $V = f(l, w, d)$ which identifies volume as the function of length, width, and depth.
- Derived data: representing results of derivation rules, e.g. Volume (V) = x cubic meters (m^3).

Such derivation rules permit computing all necessary information for environmental performance assessment. Accordingly, environmental performance can be assessed with respect to predefined criteria. The framework for the model is illustrated in Figure 3.

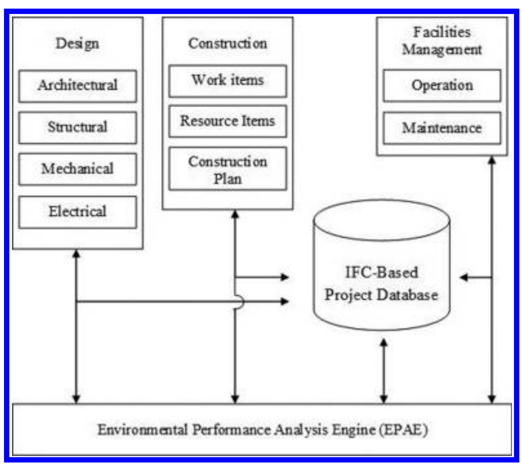

Figure 3. Model framework.

Consider, for instance the reinforced concrete footing foundations of a built facility. The following example briefly illustrates the technique for calculation of probable waste and consumed energy for excavation for these footings. Consider a zone of dimensions (*l, w*) = (*15 m, 20 m*) where *l = length, w = width,* within a construction site. Assume this area has to be excavated to a depth (*d*) = (*1.5 m*). Assume 4 concrete footings are to be constructed within this area. The dimensions for a single footing are (*l, w, h*) = (*1.5 m, 2.0 m, 0.5 m*). The volume of concrete prepared for casting in place was $7\ m^3$. The following are rule bases for environmental performance assessment:

- Energy consumed for excavation equals $32\ kWh/m^3$ (Bozdag & Secer 2007).
- Waste is calculated using the rule/formula $Waste\ (\%) = (M_{mixed} - M_{designed}) / M_{designed}$

Accordingly, the EPAE calculates the following calculations:

The development of this data model entails the following steps:

- Detailed analysis of the three interacting systems of systems to identify different stakeholders, system boundaries, system attributes, system interfaces, interactions, etc, in order to arrive at a useful model for analyzing construction products and construction processes taking into special consideration the requirements of the environmental SoS as a system of interest (SOI).
- Documentation of this analysis using the conventions of one of the standard systems engineering modelling languages, typically the *SysML*, designed specifically for systems engineering.
- Development of the Environmental Performance Assessment Engine (EPAE) with the necessary rules and metrics.
- Full automation of the model through the development of a special software package that is interoperable through IFC compliance.

Table 1. Sample data processed within EPAE engine.

	Derivation rule	Derived data
Volume of footing	*V = l* w* h*	*V = 1.5 m3*
Zone area	*A = 15 * 20*	*A = 300 m2*
Material waste	*W = (7–(4*1.5))/(4*1.5)*	*W = 16.7%*
Excavation energy	*E = 32*A*d*	*E = 14400 kWh*

These processes of system analysis and development should aid in realizing a wide range of benefits, including, among many others:

- Facilitation of visualization and process transparency across virtually all elements and processes of a typical construction project, thus enabling not only sustainable construction, but also construction process optimisation and reengineering.
- Eliminating wasteful practices and activities.
- Identifying and activating a useful set of relevant metrics for overall project and process control.

5 CONCLUSIONS AND FUTURE WORK

The construction industry has witnessed rapid and dramatic changes during the last two decades, and there still are several areas that require studying, analysis, and optimisation. This paper outlined a framework for developing a BIM-oriented data model for enabling sustainable construction in practice. This research is initiated by the authors capitalizing on the meticulous power of systems engineering that has been exploited by many industries other than the AEC, and on the power of BIM and IFCs, which are rapidly transforming the construction industry. Both the detailed systems analysis and the model development are on their way.

The research is expected to unleash several areas for improvement within the current business-as-usual of most industry entities and practitioners, not only for the benefit of sustainable construction, but for other areas as well.

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An approach to semantic modelling of activities in construction

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ABSTRACT: Documents that support design, construction and other stages of the life cycle of buildings and other facilities, as for example building standards and codes, can be considered as composed of parts that describe products, activities and/or services. Although in some cases non-textual means are employed (e.g. tables, diagrams, schemas), a significant part of the information contained in such documents is expressed through natural language sentences. In this paper, we present an approach to capture the semantics of textual activity-related information that can be used for information retrieval and knowledge management in the construction sector. This approach is based upon the general knowledge representation paradigm of semantic networks, and builds on previous work about the semantic modelling of product information. The paper describes the repertoire of representational means, concepts and semantic relations (or semantic roles), that are used for representing the semantics of activity-related information, and illustrates their use in a query-answer game that has as input documents semantically annotated according to the approach. Finally, we comment on the main characteristics of a Query-Answer System (QAS) that we are implementing for doing these tasks with ease.

1 INTRODUCTION

In the construction sector, and also in other technical sectors, the contents of most of the documents used are articulated around either the description of products or the description of activities. In this way, the documents that support design, construction and other stages of the life cycle of buildings and other facilities, as for example building standards and codes, can be considered as composed of product-centered and activity-centered parts, depending upon which is the focus of attention of their contents.

Product modelling in general and semantic modelling of information describing products in the AEC industry have been the object of important research and development efforts in the last decades (IAI 2010, Lima et al. 2003, Wetherill et al. 2002). This is not the case for semantic modelling of information about processes, tasks and activities (hereafter, activity-related information), that keeps lagging behind.

For activity-related information we refer to the wide variety of information that describes: (1) the activities to be performed, (2) the structure of activities as a sequence or concurrence of sub-activities or actions that can or cannot be repeated in an iterative or recursive way, (3) the participants or entities that take part in activities (as, for example, the agent or entity that causes actively or performs an activity, tools or equipment that should be used, their results, etc), (4) the circumstances in which the activities are carried out, that refer to the situational embedding (e.g. to their spatio-temporal or environmental embedding).

A significant part of such information is expressed through natural language sentences, although in some cases other non-textual means of expression are used, such as tables, diagrams, schemas, etc. In this paper, we present an approach to capture the semantics of textual activity-related information that can be used for information retrieval and knowledge management in the construction sector. This approach is based upon MultiNets (Helbig 2002), a universal method for the semantic representation of natural language expressions.

As in MultiNets, our approach can be included into the general knowledge representation paradigm of semantic networks. However, our approach adapts such general representational means to the technical domain of activity-related information and builds on previous work about the semantic modelling of product information in the construction sector (Bravo-Aranda et al. 2008).

Section 2 outlines the general approach to semantic modelling and knowledge representation we are working on. As semantic relations are the most important representational means, section 3 of the paper is devoted to the repertoire of semantic relations specifically connected with activity-related information and its semantic representation. We are developing a classification of technical activities, based upon their semantic characterization, which permits to associate certain structure of semantic roles (valency frame) with every activity belonging to each class. In section 4, we report on the tasks we are undertaking to validate the approach, discuss an example, and comment on the main characteristics of a query-answer system that we are implementing. Finally, we present some concluding remarks in section 5.

2 OUTLINE OF THE APPROACH

Several disciplines in the field of Artificial Intelligence, mainly knowledge representation and Natural Language Processing (NLP for short), are concerned with the problem of representing the semantics of natural language expressions. As mentioned above, our approach is based upon Multinets, an universal method for knowledge and meaning representation in NLP systems that is very well documented in (Helbig 2006).

As in Multinets, our approach is based on the use of a repertoire of representational means that: (1) are designed to allow for an adequate description of the core meaning of natural language expressions; (2) are independent of any specific language and so it constitutes a sort of interlingua, and (3) can be included into the general knowledge representation paradigm of semantic networks. However, our approach adapts such general representational means to the technical field of product, activity and service-related information. An outline of the knowledge representation system (KRS) used and the semantic representation of product-related information have already been presented in (Bravo-Aranda et al. 2008), and so this section only recalls the fundamental elements of the general approach.

Concepts, represented as nodes, and semantic relations, which are represented as labelled-arcs, are the basic structural elements in the knowledge representation paradigm of semantic networks. However, our approach utilizes a knowledge representation framework that consists of the following main components:

- An ontology of conceptual entities that collects the semantic classes or sorts of concepts. Every concept is classified as belonging to a specific sort.
- A hierarchy of semantic relations and functions that allow for describing the meaning of individual phrases and sentences as semantic connections between nodes. In this way, the arcs of a semantic network may only be labelled by members of the fixed set of relations represented by this hierarchy.
- Semantic features that additionally characterize the internal semantics of concepts and relations.

Semantic relations and functions are properly described by means of the following characteristic elements: (1) a label name as expressive as possible; (2) a signature specifying the domain and range sorts of the concepts on which the relation or function is defined; (3) a verbal characterization of the relation or function; (4) specification of typical question patterns that can be used in a question-answer game or to enquire about the validity of that relation; (5) a detailed explanation of the meaning and intended use of each relation and function.

In the case of activity-related information, a sub-hierarchy of semantic relations is provided that allow for the representation of semantic roles of participants and circumstances, and also for other semantic connections of interest. A fundamental criterion for including a representational element into the repertoire is that it should permit to give answers to one or more meaningful query patterns in the field of activity-related information in construction.

As semantic relations are the most important representational means, the next section of this paper is devoted to the repertoire of semantic relations specifically connected with activity-related information and its semantic representation.

3 SEMANTIC ROLES USED IN REPRESENTING THE MEANING OF ACTIVITY-RELATED INFORMATION

In the ontology of conceptual entities, activity is a class derived from the more general sort situation. Situations or states of affairs represent the modes of being of objects or the changes they undergo. As it is the case for most upper ontologies, situations are classified into states, for static situations, and events for dynamic situations (see Figure 1 below). Events are in turn sub-classified into activities (also termed actions), i.e. events that are actively carried out by an agent, and happenings, that are events having causes not associated with an agent.

Every situation, state or event, is considered as a conceptual entity in itself, and so it corresponds to a node in the semantic network. Textual information that refers to a specific situation may include information describing both the objects involved in the situation and other situations connected with it. In all cases, we use semantic relations and functions for representing the meaning of such connections. For example, objects taking part in a situation, or participants, are linked to that situation by means of appropriate semantic relations. However, and as it is usual in the field of Natural Language Processing, semantic relations are named according to the cognitive roles (Fillmore 1968), or semantic roles, that objects have in a situation (for instance, AGT for the agent or entity that carries out an activity).

Figure 2 shows the set of semantic roles that we are presently using for semantic representation

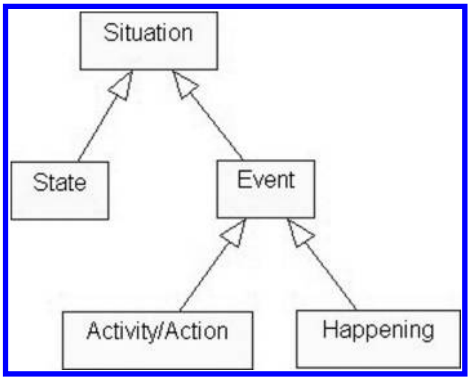

Figure 1. Subhierarchy of the situation sort.

of situation-related information. Most of these semantic roles were adopted from the literature on this topic, although in several cases we have simplified the existing ones (by removing roles that represent what we consider only slightly different semantic distinctions or that are highly improbable in technical domains), and in a few cases we have proposed new roles, to capture relevant semantic connections in technical domains.

In Figure 2, semantic roles are grouped into several thematic areas. In the following paragraphs, we briefly describe the meaning of the semantic roles included in the repertoire. From left to right, we distinguish:

- Semantic relations that enable to classify situations as instances or subclasses of a (more generic) class of situations, that are denoted, respectively, by the roles INSTS and SUBS.
- Semantic relations for the structural description of situations, including roles for: (1) the relation between a sub-activity and the activity of which it is a part, PARTS role; (2) the connection between activities through outputs/inputs, CONNS role; (3) the conditions for a situation, COND role; and (4) the relation between

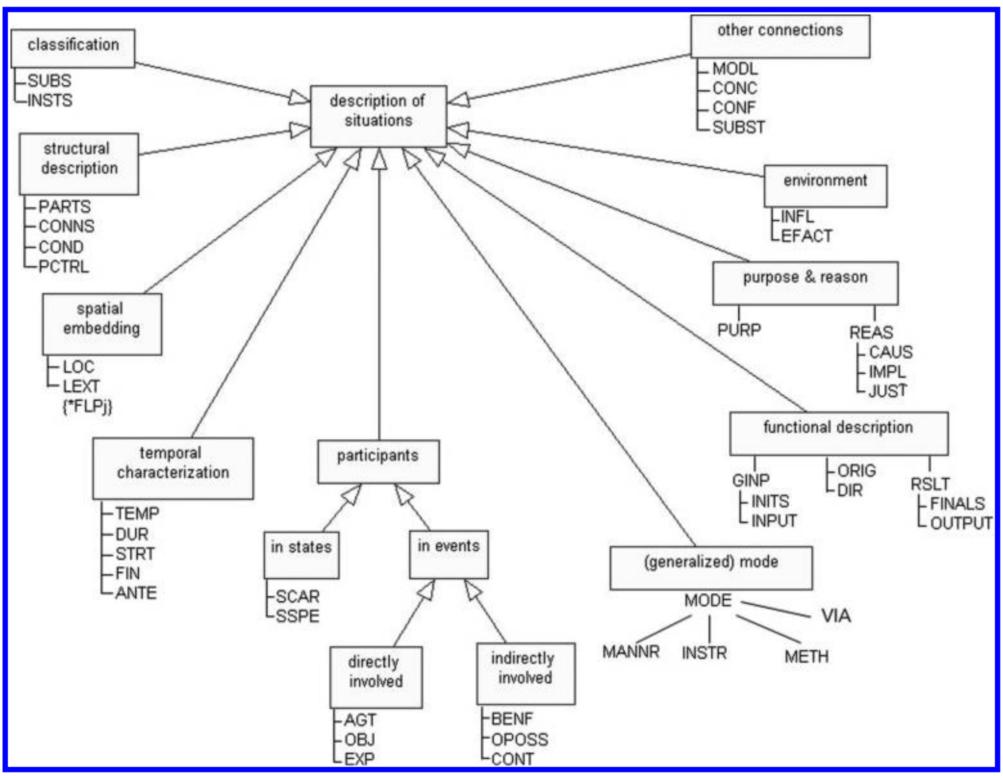

Figure 2. Classification of semantic roles.

a parameterized situation (see the example in section 5) and the rule set that controls its parameter's possible values, PCTRL role.

- Semantic relations to describe the spatial context of situations, including semantic roles for: (1) the location where a situation holds or an activity is carried out, LOC role; (2) the spatial extent of a situation, LEXT role; and a set of functions, denoted by $*FLP_j$, that generate spatial regions (locations) from objects (for instance, the local function *ON generates a specific location when applied to a concrete object, as in the phrase "on the table").
- Semantic relations for temporal characterization of situations: (1) specification of the time interval, or moment, within which a situation holds, TEMP role; (2) the duration of a situation, DUR role; (3) the temporal beginning/end of a situation, specified, respectively by the roles STRT and FIN; and (4) temporal precedence of a situation that holds before another, ANTE role.
- A set of semantic relations for participants, i.e. the objects that take part in states or events, that distinguish: (1) semantic roles for participants in states, including the role that connects a state to an object which is in this state, SCAR role, and also the role that connects a state to an entity that represents the value that specifies this state, SSPE role; from (2) five semantic roles for participants in events: (1) a role for the connection between a situation and an agent, or entity that originates, sustains or gives rise to that situation, AGT role; (2) a role for the relation between an event and an object that is directly acted upon or affected by that event, OBJ role; (3) a role for the connection between a situation and an object that experiences it, EXP role; (4) roles for the beneficiary of a situation (the beneficiary of a situation is usually not immediately participating in the situation and is also not changed by it, but he/she/it receives some benefit from the situation), BENF role; and (5) for an entity that opposes a situation, OPPOS role.
- Several semantic roles for the mode by which an activity is carried out or a state is sustained. These roles are generalized by the semantic relation MODE that comprises the roles: MANNR, for the qualitative specification of the manner of a situation; INSTR, for the instruments used; METH, for connecting an activity or state to the method by which it is carried out or sustained (a method can be either referred to by its name or specified by a sequence of actions); and VIA, that connects an activity to a spatial path taken or material medium used.
- A set of semantic relations that enables to functionally describe an activity. In this branch, we include three subgroups of roles for connecting an activity to: (1) an entity that is processed by that activity, INPUT role, or an entity that represents the initial state which is its starting point, INITS role, that are both subsumed into the general role GINPUT; (2) an entity that is obtained as a result of that activity, RSLT role, that comprises the sub-roles OUTPUT and FINALS for, respectively, an entity that is obtained as a product and the final state resulting from that activity; and (3) its local, human or informational origin, ORIG role; and the local, human or informational entity to which the activity is directed, role DIR.
- A set of roles for: (1) the semantic relation between a situation (typically an activity) and its purpose, PURP role; and a group of semantic relations for the general reason of a situation, REAS role, that can be explained causally, CAUS role; logically, IMPL role, or by other type of justification (such as social convention), JUST role.
- Semantic relations to describe the environmental and interaction conditions in which a situation holds. These relations correspond to the roles: (1) INFL, which connects a situation to the ambient conditions, or to other circumstances concerned with mechanical, chemical or any other kind of influence in which a situation holds: and (2) EFACT (effect as action), for connecting a situation to circumstances concerned with effects of actions imposed on that situation.
- Finally, the so called "other connections" subarea forms a miscellaneous group of four semantic relations. From top to bottom, these relations are: MODL, that specifies the modality of a situation (in technical domains, the modality is mainly used to restrict the meaning of sentences that express the performance of an activity as mandatory, recommendatory, etc.); CONC (concessive), to indicate the connection between a situation and a circumstance that seemingly opposes that situation; CONF, expressing the conformity of a situation with a general frame (for instance, according to normative regulations); and SUBST, that is used to express that a situation or object is substituted for another situation or object.

4 A QUESTION-ANSWER SYSTEM FOR ACTIVITY-RELATED INFORMATION RETRIEVAL

To validate the utility of the approach, we are undertaking the following tasks: (1) preparation of a repository of selected technical standards and codes, (2) definition of an XML schema for semantic annotation of textual activity-related information, (3) manual annotation of the activity-centered parts included in several documents, (4) development of a question-answer system for activity-related information retrieval; and (5) validation tests and results evaluation. In the following, we comment on the state of these undertakings that are still in progress.

We have prepared a varied collection of standards. This collection includes standards of different types (e.g. design standards and test standards), referred to different sub-domains of the AEC sector, from different regulatory organizations, and in different languages (e.g. in English and Spanish).

A previous XML schema for semantic annotation of textual information describing products was extended to also enable semantic annotation of activity-related information. This extension consisted in including in the schema the set of concepts, semantic relations and features defined as semantic representational means for activity-related information.

Although we hope that tools for assisting in the task of semantic annotation are soon available, for the moment a hard work of manual annotation is necessary to obtain semantically enriched text. We have annotated parts of several documents in the repository. Figure 3 shows a subsection of the ASTM standard D 1883-07 (ASTM 2007), and its annotated version in Figure 4.

Section 9 of that standard specifies a method for the CBR bearing test (i.e. the whole contents of section 9 can be annotated by the role METH). Subsection 9.1 is an instruction because it expresses an activity to do as the first step of the method. This basic activity (i.e. "Place a surcharge of weights on the specimen") is parameterized in terms of the specific value of surcharge load to use (i.e. by the QMOD role, that specifies a quantity associated with the concept "surcharge of weights") depending on certain conditions (specifically, the value of surcharge load to use is different if a pavement weight is specified or not, or if the specimen has been soaked previously). As it is usual, the parameter that completes the

> **9. Procedure for Bearing Test**
>
> 9.1 Place a surcharge of weights on the specimen sufficient to produce an intensity of the loading specified; if no pavement weight is specified, use 10-lbf (4.54 kg) mass. If the specimen has been soaked previously, the surcharge shall be equal to that used during the soaking period. To prevent upheaval of soil into the hole of the surcharge weights, place the 5-lbf (2.27-kg) annular weight on the soil surface prior to seating the penetration piston, after which place the remainder of the surcharge weights.

Figure 3. Section 9.1 of the ASTM standard D 1883-07.

activity expression is controlled by a set of rules (we annotate the part containing this set of rules with the PCTRL role). Each rule provides a value of surcharge load (THEN role of the rule) for a given condition (RCOND role of the same rule). Last part of subsection 9.1 establishes a method for this activity, i.e. a concrete way of doing the activity, as a sequence of three actions (we annotate these actions with the PARTS role, and the fact that one action precedes another is indicated by the ANTE role connecting them), and it explains the purpose of this method (i.e. "to prevent upheaval of soil into the hole of the surcharge weights" is annotated by the PURP role). A representation of the semantic network obtained from interpreting the annotated text is shown in Figure 5.

From the example above, it can be seen that the annotation language enables to convert a technical document into a semantically enriched XML document that constitutes a knowledge base. This kind of knowledge bases can be used to answer a wide variety of meaningful queries.

Another characteristic of this mark-up language is that the granularity of annotation, and so the level of detail of the semantic descriptions that can be obtained, can be varied from coarse to a very fine and detailed one.

Once an annotated version of a document is obtained, the standard query language XQuery (XQuery 2010) can be directly used to formulate queries. XQuery is a functionality that can be found in XML commercial environments, such as XMLSpy from Altova.

In relation to the example presented above, by using XQuery it is possible to formulate queries and obtain answers as the following: (1) **Q**: According to which method is the <CBR bearing test> carried out? **A**: [The complete contents of section 9]; (2) **Q**: What's the purpose of <the method of <activity 1>>? **A**: "To prevent upheaval of soil into the hole of the surcharge"; and (3) **Q**: What's the amount of <surcharge of weights> if <no pavement weight is specified>? **A**: "10-lbf (4,54 Kg) mass".

However, direct formulation of queries in XQuery requires an exhaustive knowledge of both the annotation schema and the query language. In order to avoid these drawbacks, it is necessary to develop a user interface that enables the user to formulate queries in a way as close as possible to natural language.

We are now implementing a question-answer system with the following main characteristics:

- It is based, in a flexible way, on the repertoire of semantic representational means that form the KRF: ontology of conceptual entities, hierarchy

```
<docDiv id="9"> <title id="9"> 9. Procedure for <concept id="59" sort="act"> Bearing Test </concept> </title>
 <infoBlock id="9">
  ...
   <srel id="4" type="METH" refid="59">
    <concept id="60" sort="act">
     <srel id="5" type="PARTS" refid="60"> 9.1
      <concept id="61" sort="act" par="T">
       <srel id="6" type="SUBS" refid="61">
        <concept id="62" sort="act"> Place </concept> </srel>
        <srel id="7" type="FINALS" refid="61">
        <concept id="63" sort="st">
         <srel id="8" type="SCAR" refid="63"> <srel id="9" type="OBJ" refid="61">
          <concept id="64" sort="co"> a surcharge of weights </concept> </srel> </srel>
         <srel id="10" type="SSPE" refid="63"> <srel id="11" type="DIR" refid="61">
          <srel id="12" type="LOC" refid="64">
           <concept id="65" sort="l"> on the specimen </concept> </srel> </srel> </srel> </concept> </srel>
    </concept> </srel>
       <srel id="15" type="PCTRL" refid="61">
        <concept id="68" sort="rule" setof="T">
         <srel id="16" type="PARTI" refid="68">
          <concept id="69" sort="rule"> sufficient to produce an intensity of the loading specified </concept>
         </srel>]
         <srel id="17" type="PARTI" refid="68">
          <concept id="70" sort="rule">
           <srel id="19" type="RCOND" refid="70"> <srel id="20" type="COND" refid="61">
            <concept id="71" sort="st"> if no pavement weight is specified. </concept> </srel> </srel>
           <srel id="21" type="THEN" refid="70"> <srel id="22" type="QMOD" refid="64">
           <concept id="72" sort="m"> use 10-lbf (4.54 kg) mass </concept> </srel> </srel> </concept>]
         <srel id="18" type="PARTI" refid="68">
          <concept id="73" sort="rule"> if the specimen has been soaked previously, the surcharge shall
          be equal to that used during the soaking period </concept> </srel>] </concept> </srel>
       <srel id="23" type="METH" refid="61">
        <concept id="74" sort="act">
         <srel id="24" type="PURP" refid="74"> <concept id="75" sort="st"> To prevent upheaval of soil into
          the hole of the surcharge weights. </concept> </srel>]
         <srel id="25" type="PARTS" refid="74">
          <concept id="76" sort="act"> place the 5-lbf (2.27 kg) annular weight on the soil surface </concept>
         </srel>
         <srel id="26" type="PARTS" refid="74"> <srel id="27" type="ANTE" refid="76"> prior to
          <concept id="77" sort="act"> seating the penetration piston </concept> </srel> </srel>
         <srel id="28" type="PATS" refid="74"> <srel id="29" type="ANTE" refid="77"> after which
          <concept id="78" sort="act"> place the remainder of the surcharge weights. </concept> </srel> </srel>
        </concept>
       </srel>
      ...
      </concept>
    ...
   </srel> </infoBlock> </docDiv>
```

Figure 4. Annotated version of Section 9.1 of the same ASTM standard.

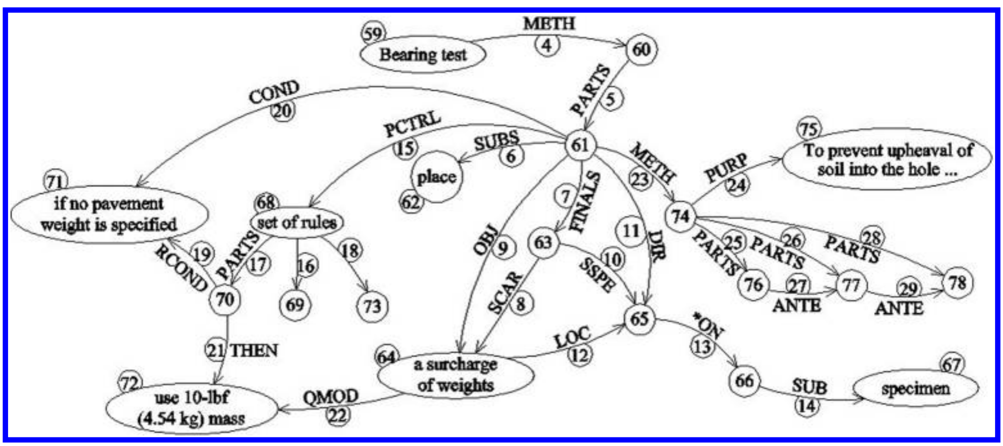

Figure 5. Semantic network from interpreting the annotated text.

of semantic relations, functions and other semantic features.

- It uses as knowledge base a repository of documents annotated according to the schema.
- It is internally supported by the use of XML-based technologies, such as XQuery.
- It includes a user interface that enables to formulate queries in a controlled subset of natural language.
- It does information retrieval at two distinct levels: at the level of relevant documents and also at the level of relevant pieces of information therein.

5 CONCLUSIONS

A thorough and complete conceptual understanding of activity-related information is considered a necessary prerequisite for developing a semantic knowledge representation system for this complex kind of information. Over other more structured knowledge representation formalisms, semantic networks have the advantage of enabling a representation that can be made to fit precisely the contents to represent. This is very convenient because the information about activities in technical documents only refers to those aspects that are relevant.

The repertoire of representational means presented in this paper constitutes a Knowledge Representation Framework (KRF), and so it is a contribution to the construction of the knowledge representation system that is needed. Among the characteristics of the KRF, we highlight the following:

- It uses a repertoire of representational means that are independent of any particular language and so it constitutes a sort of semantic Interlingua.
- The repertoire of representational means allow for an adequate description of the core meaning of activity-related sentences, and it consistently extends a previous framework for semantically describing the contents of product-related information.
- It is oriented to information retrieval because each semantic relation in the repertoire has one or more associated question patterns that can be used in a question-answer game or to enquire about the validity of that relation in a given context.
- Based upon the representational elements, it is relatively easy to define a mark-up language for semantic annotation of textual information.
- The granularity of annotations, and so the level of detail of the semantic descriptions that can be obtained, can be varied from coarse to a very fine and detailed one.
- It makes feasible to implement computer programs for information retrieval in which queries are formulated in a controlled subset of natural language.

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Concept of an information framework for management, simulation and decision making in construction projects

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ABSTRACT: Decision making in construction planning and management requires access to information about latest building and construction plans as well as respective controlling information in the context of the construction process. Until today, this information resides in engineering and management models maintained separately on owner and constructor side. Despite the progress in model-based planning the application-specific models still vary in focus, conceptualization, structuring and detailing and still lack bridging concepts and interoperability technologies. This paper presents the conceptual development of a Management Information System to enable decision making on the different management levels within the owner and the constructor organisations. Backbone of the system is an open service platform and a layered ontology-based model framework providing for the build-up of a distributed multi-model information space. Central to that multi-model space are process models that inter-relate various engineering and management models in regard to the planning, production and controlling tasks within the owner and the constructor organisations. The paper discusses (1) the ontology-based multi-model framework, (2) the use of central platform services providing for horizontal, vertical and longitudinal integration of the information models, and (3) the use of the overall platform to dynamically model construction processes and verify them in simulations.

1 INTRODUCTION

Today's project planning and management applications are still focused on selected tasks of architects, engineers and managers on either the owner's or the constructor's side. The software systems lack an interoperable view on the overall planning and management processes and hence they do not support efficient reuse of the model-based information.

Particularly, for construction planning there is little support to efficiently utilize the information from building design and ongoing construction execution to evaluate consequences and risks of current planning decisions. Firstly, there are numerous interoperability problems remaining horizontally among the management and engineering disciplines involved in the project. Secondly, there is very little support for vertical model transitions:

- either *top-down* when detailing a general project plan to evaluate the estimated resource and set-out performance parameters
- or *bottom-up* when on-site progress information must be aggregated for higher level controlling decisions or when results of detailed model analyses must be propagated to subsequent planning tasks.

Whilst criticised for some decades (Sriram 1998), there is still little progress in overcoming the owner—constructor interoperability problems. Research work has mainly targeted the design processes or project management issues, focusing on schedules and costs. Efforts in 4D and nD modelling have tackled some of the challenges in BIM-centric manner (Aouad et al. 2007, Gao & Fischer 2008) but have not analysed in depth the interplay of design, construction management and construction execution processes in their mutual interrelationship

Given these shortcomings, the German research project Mefisto develops a *Management Information System* that integrates model-based information in a distributed multi-model space to support decision making in different disciplines as well as on different management levels of the project organisations (Scherer 2009).

Backbone of the envisaged system is a semantic service platform and a layered ontology-based model framework that defines a multi-model space representing core concepts of construction planning and management within most common application models as well as various useful process related model combinations.

There are three general types of model interrelations distinguished:

– *horizontally* between models of owners and constructors, with different application domains and model formalisations,
– *vertically* between models representing different levels of abstraction supporting decision making on different management levels as well as
– *longitudinally* between model versions generated at different points in time.

Central to the multi-model space is a process model that provides for inter-relating the engineering and management models in regard to planning, production and controlling tasks.

The semantic service platform in turn provides dedicated information logistics and analysis services to realise the envisaged integration of the disjoint information on client and contractor side, make it interoperable, improve efficiency of collaboration processes and, last but not least, increase trust to enable true partnership construction.

In this paper we focus on the ontology-based multi-model framework, the use of central platform services enabling horizontal, vertical and longitudinal integration of the information models and the use of the overall platform to dynamically model construction process and verify them in simulations.

2 MULTI-MODEL FRAMEWORK

The information backbone of the Mefisto platform is developed in anticipation of the fact that not all relevant project data can be structured in an all-encompassing schema. To handle application models of different engineering and management disciplines in different formalisations a layered ontology-based model framework of four layers is being developed providing a general ordering schema, explicit inter-model relationships and a set of supporting information logistics and management functions.

2.1 *Framework overview*

Central to the model framework is the *Construction Core Ontology.* It defines core concepts of construction planning and management in accordance to selected standardized as well as non-standardized data schemas (general schemas). This approach allows for the exchange of application models such as project schedules and building specifications using common data formats, while guarantying a basic level of interoperability.

Moreover, the model framework defines additional link concepts and standard model transformations to explicitly model the horizontal, vertical and longitudinal interdependencies.

The common data schemas are complemented by a schema specification for a generalised information container, named Mefisto Container, and application-specific Multi-Model Definitions (MMD). The *Mefisto Container* represents a logical envelop for handling distributed, yet inter-related application models and corresponding link models as a single information resource. The information requirements for such resources are defined by the *Multi-Model Definitions.* They contain, in turn, *Elementary Model Definitions* (EMDs) specifying model subsets and additional constraints based on the selected general schemas for particular application areas. They also define *Elementary Link Models* with complementary inter-model relations and integrity constraints that need to be fulfilled by the overall multi-model composite.

On top of the Construction Core Ontology the model framework defines a *Project Collaboration Ontology*. On a metadata level it provides for the semantic description of the content, the formalisation and the interrelations of the multi-models in an information container. Hence, it allows for systematically archiving, retrieving and re-using multi-model resources on the Mefisto platform in human as well as in computational processes.

2.1.1 *Construction Core Ontology*

The first four layers of the framework define the Construction Core Ontology that reflects core concepts of standard as well as non-standard data schemas. Whilst a large number of core construction data can already be captured within IFC project models, there are several national standards such as the German GAEB DA (GAEB 2009) for work specifications as well as application-specific schemas (e.g. for scheduling) that are used more frequently. Moreover, for some of the application areas of construction planning and management such as the design of infrastructures, material logistics and production assembly on the construction site no standard data schemas are available.

For the exchange of information on the Mefisto platform general model schemas as well as complementary model definitions are defined for all of the modelling domains. Furthermore, the core concepts of these schemas and the link concepts are also represented in a formal ontology that supports the identification, integration, verification and complementation of the distributed model information.

2.1.2 *Construction processes*

The first layer of the framework represents the construction processes to plan, execute and control a construction project. Depending on the primary result of the process we differentiate between *material processes* comprising production, transportation and erection tasks on the construction site and *information processes* combining tasks to plan, coordinate and control the material processes. This differentiation is important because the first type of processes can only be virtually represented on the platform and simulated by appropriate simulation/analysis tools, whereas the second can be assembled into executable workflows.

As illustrated in Figure 1 the construction process model takes a key-position within the model framework. In our process-centred approach it allows for interrelating model-based information from different engineering and management domains in integrated business process models. Within the process, the material process elements allow for interrelating building elements and complementary quality specifications from related application models and capturing their possible status. Moreover, the material process elements provide for allocating the human, informational, material and technical resources required for the production of an element. In turn, information processes elements allow for relating input of general product requirements or target performance indicators for a process with the detailed product specifications developed by the process, or respectively, the actual performance indicators recorded by the process.

Furthermore, as indicated in Figure 1 the integrated construction process model provides a sound basis for an efficient assembly of simulation models.

Chapter 4 outlines the transition from construction process to construction simulation models discussing the necessary model transformations.

For the Mefisto platform a Semantic Web Ontology is developed that inter-relates the process elements with corresponding application models forming an integrated process model. Extending conventional scheduling models with reusable process modules, integrity constraints and composition and configuration rules it supports the identification, retrieval and integration of related multi-model information as well as the verification and optimisation of the integrated construction process models (Rybenko et al. 2010).

2.1.3 *Construction products and resources*

The second layer defines the core concepts that reference concrete construction products and resources. The concepts are organised in three model domains:

The domain of *Building Information Models* (BIM) focuses on the functional, geometrical and topological description of the building elements and their composition. All data schemas for the building model EMDs are developed based on the IFC Model (Liebich et al. 2005).

The domain of *Construction Site Models* (CSM) comprises the site infrastructure elements, the construction materials, the pre-fabricated building elements as well as construction machinery and equipment together with their basic geometrical, mechanical and economical properties. There was no formal models identified that satisfied the information requirements of construction site model EMDs. Hence, a new data schema is being developed which should follow the IFC paradigms.

The domain of *Organisation Models* (ORM) defines organisational actors and resources as well as their interrelations. Depending on the application area and the level of detail these concepts may be used to model supply networks or reporting structures of a project as well as the deployment of works on the construction site. For the exchange of organisational information a new data schema is developed that builds upon previous research in the German BauVOGrid project (Hilbert et al. 2010) and proprietary schemas of the software developers in the project consortium.

2.1.4 *Qualities of products and processes*

The third layer comprises concepts describing the qualities of construction products in the building model and of construction processes in the construction process model. Again the concepts are organised in three modelling domains:

The domain of *Specification Models* (SPM) subsumes formal and informal models describing additional qualitative properties of building products

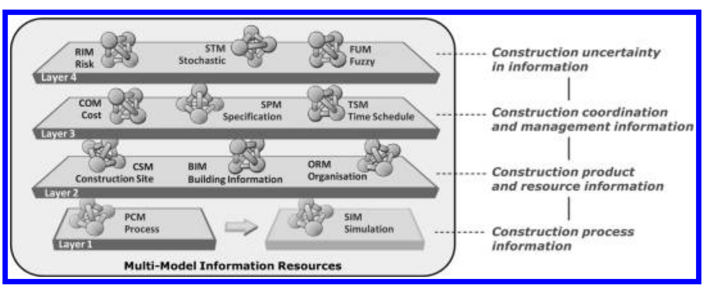

Figure 1. Layered structure of the Construction Core Ontology capturing the multi-model information resource domain.

and processes, such as functional, material or regulatory requirements. In principle, specification models comprise functional building requirements, work specifications as well as building element catalogues. However, the Mefisto project first of all focuses on work specifications in unit price contracts, which are formalised according to the German standard GAEB DA XML (GAEB 2009).

The domain of *Cost Models* (COM) comprises all models that allocate monetary values to building products and processes e.g. in estimating, calculating, contracting and construction controlling. Until today such cost information is handled separately by owners and contractors with regard to very different building and process elements. In Mefisto the interlinking of building and process elements with corresponding quality models now allows for the synchronisation of these cost models in selected application areas such as contracting, progress reporting and billing. The definition of respective EMDs also uses the GAEB DA specification (GAEB 2009).

The domain of *Time Schedules* (TSM) represents the core concepts of common scheduling models including elements such as activities and sequential relations as well as resource loads and calendars. The EMDs for the Time Schedule Models are defined using a proprietary data schema developed in accordance to selected commercial scheduling application to provide for the preliminary design as well as for the reuse of construction process models in these applications.

2.1.5 *Uncertainty models*

The fourth layer contains uncertainty models that are used to forecast and evaluate design and management decisions reflected by the models on the lower levels. Again three different modelling domains are examined, distinguishing among *risk models* representing various project risks as well as *stochastic* and *fuzzy models* that are used to explicitly capture the uncertainties particularly involved in the design of construction schedules and the estimates of product and process qualities such as costs and durations.

2.2 *Project Collaboration Ontology*

The overall multi-model logistics and the operability of the platform are grounded on the consistent use of the *Project Collaboration Ontology*. It provides first of all metadata-information on the multi-model definitions but also describes the possible use of the respective models in construction planning and management. Moreover, it allows for the documentation and the coordination of information processes in which the multi-models are created, transformed, altered and used by software services and users.

On the platform, elementary and composite models are exchanged using Model Containers. Within the context of the model containers the Project Collaboration Ontology provides for the semantic annotation of the model content on three levels (Fig. 2)

- *Model elements*: If necessary, particular model element specifications within a model can be complemented with additional annotations inside or outside that model.
- *Elementary application model*: The elementary application models are described on meta level in regard to the model domain, the core objects and the level of abstraction as well as the respective general schema and model definition.
- *Composite model*: Complementary to the descriptions of the elementary models the Model Container can also hold meta-information about the corresponding link model. Moreover, it can capture additional content and contextual information describing the focus and the possible visualisations of the composite model as well as the users and software application involved in its creation process.

Figure 2 shows the inter-relationship among the multi-model resources and the collaboration ontology components. The information flow will be realised via Mefisto Containers that can encompass individual model objects of one or several domain models, a single model schema or EMD or, quite frequently, a sophisticated Multi-Model Definition (MMD).

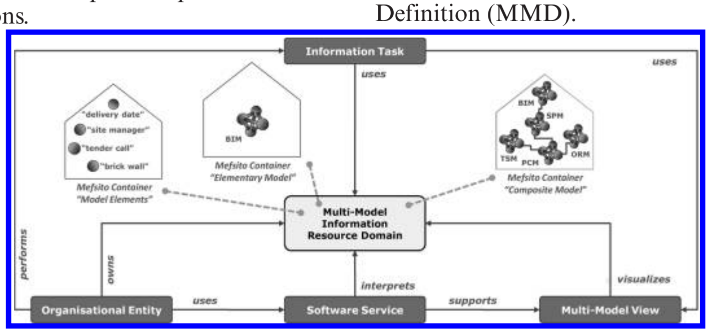

Figure 2. Integrated information management based on the shared collaboration ontology of the ICT platform.

For uniform annotation of the Model Containers general domain as well as project-specific ontology components can be published on the Mefisto platform. From the perspective of the multi-model resource they allow for the specification of:

– the *information tasks* in which the multi-models are created, transformed, changed or re-used
– the *software services* that can read, interpret and create certain multi-models
– the *organisational entities* that have access and user rights to certain multi-models
– the *multi-model views* that provide a most adequate visualisation of certain multi-models.

3 FRAMEWORK IMPLEMENTATION

The implementation of the described multi-model framework in the Mefisto project recognises the fact that model data is distributed among the parties participating in a construction project and is therefore subject to various constraints, including security and confidentiality considerations.

3.1 *Mefisto ICT platform architecture*

The suggested overall technical architecture of the Mefisto platform is shown on principal level in Figure 3. It features a hybrid SOA-based system integrating local legacy applications and various platform services via standard web service and .NET technology. Typical legacy applications comprise 3D CAD, scheduling, quantity take-off, ERP and PPM systems. In the scope of the Mefisto project these will include for instance the 3D parametric CAD system SolidWorks, the new integrated ERP system RIB iTWO, the integrated monitoring and controlling system GRANID and several complex simulation tools such as Plant Simulation and AnyLogic.

Whilst this is overall a well-known approach to the development of distributed web-based platforms, there are three features specifically targeting client-contractor partnership that have to be mentioned.

Firstly, users are consistently treated as part of a virtual organisation in terms of authentication, authorisation and access rights by means of a role-based approach using known standards such as RBAC and ABAC (Hilbert et al. 2010). Hence, only a minimal necessary amount of public data is shared whereas all other needed information exchange is performed by specialised role-sensitive services.

Secondly, each partner uses its own familiar tools. Communication with other partners is achieved in transparent manner using platform services integrated via dedicated plug-ins and/or web browser GUIs. Data transport is provided by means of harmonised Model Containers, created and manipulated by appropriate model management services.

Thirdly, operations are guided in process-centric manner with the help of the Collaboration Ontology providing dynamically instantiated business process objects based on predefined reference process and knowledge patterns. This approach extends earlier concepts and findings described e.g. in (Katranuschkov et al. 2006).

3.2 *Platform services*

To ensure flawless and efficient functioning of the IT platform various model management services are required. Broadly, they can be divided into basic single-model services and advanced multi-model services.

The *basic services* range from services for the realisation of relatively simple single-model queries such as reading/updating specific properties of selected model instances and model parsers to more sophisticated information logistics and model management services providing for complex model queries involving sets of modelling objects and/or attributes. Common to all these services is their generic realisation, the direct binding to the model data and the intentionally missing direct end-user access.

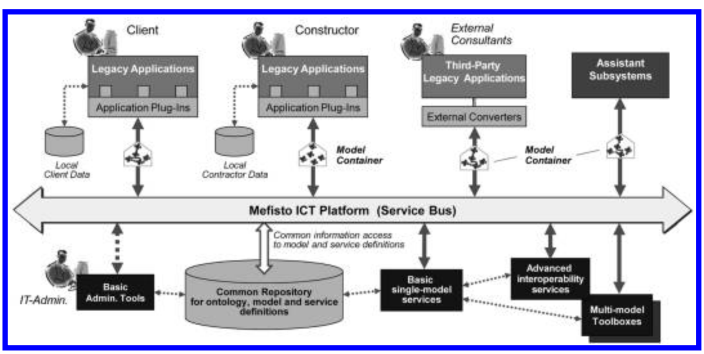

Figure 3. Architecture of the Mefisto ICT platform.

The *advanced multi-model services* can be further subdivided in interoperability services, multi-model toolboxes, assistant systems and application plug-ins.

Multi-model interoperability services are needed to support the horizontal, vertical and longitudinal model transformations discussed in the previous chapter. In particular, *horizontal* interoperability is needed when data from one or more models have to be restructured for use in another context by some other application, e.g. when using BIM data to exactly quantify and allocate work specification splits in an ERP system. *Vertical* interoperability is needed for the synthesis of detailed data for decision making on higher level. This involves various structural and functional aggregation mechanisms to create performance indicators out of the available detailed data. Such transformations may be simple, e.g. to estimate the amount of the total volume of concrete to be supplied for the casting of all columns on one building storey, but they can also be fairly complex, e.g. to estimate the time needed for a group of operations performed by a group of interacting construction teams. At last, *longitudinal* interoperability is required to support model change management when models are updated in time.

Various *multi-model toolboxes* can be envisaged in connection with the interoperability services. In Mefisto, several such toolboxes are specified for development such as (1) a process module retrieval toolbox, (2) a controlling and risk management toolbox and (3) a visualisation toolbox.

Common to all these toolboxes is their dependent use within other software components (including respectively inherited access rights to resources), the use of model data exclusively via the basic model management services and the targeted broad reusability. Realisation can vary from pure Web (.NET) services to Web services and clients as well as dedicated plug-ins.

The *assistant systems* operate on a higher level of complexity. Planned developments of such systems in Mefisto include: (1) a dynamic process configurator, (2) a construction site configurator, (3) a strategy and scenario manager for simulation tasks, (4) a collision checker for supply and assembly tasks, (5) filtering and (6) mapping editors.

Assistant systems do not provide direct administrator access as they are closely related to the actual project partners and do therefore strictly observe security and responsibility issues. They should all have full-fledged user interfaces, eventually using the services of the visualisation toolbox, and should either use local data resources or access common data exclusively via requests to respective toolbox components or basic model management services.

At last, *plug-in components* provide for the access to the Mefisto platform in legacy applications. Their primary tasks are to provide for the necessary connectivity, to read and write Model Containers and to transform these to/from the internal data structures of the respective legacy application.

4 PROCESS-CENTRIC FRAMEWORK USE

The outlined interoperability and logistics services pave the way for a variety of novel process-centred model integration and utilisation scenarios. Key components in these scenarios are the toolboxes and assistant systems for the development of construction processes as well as for the derivation of simulation models to evaluate the construction execution and logistics plans.

4.1 *Reference process knowledge modules*

Central to the Mefisto platform are the toolboxes and assistant systems for the development of construction processes in a dynamic and semi-automatic modelling approach that combines the methodologies of business process objects and reference process modelling (Baling et al. 2010).

In the context of the multi-model framework a *Business Process Object* (BPO) reflects a set of model-based information items from the multi-model space (business objects) bound to a particular planning, management or production task. A BPO can thereby be understood as an extension of the known Business Object specifications in that it enables better and more consistent binding of real-world concepts representing a product or service which is the goal of a business activity with the actual process for the realization of this activity (Katranuschkov et al. 2006).

In turn, *reference modelling* provides techniques for the systematic reuse and customization of BPOs. It organizes the tasks of information modelling in two cycles. The model development cycle includes problem definition, reference model construction as well as the subsequent model evaluation and care. The model application cycle covers the retrieval, customization, integration and the application of reference models (Fettke & Loos 2004).

To support reference modelling of construction process, BPOs are extended towards reusable process knowledge modules in two ways (Scherer 2009).

Firstly, the BPOs are packaged into generic parameterised reference process modules defining recurring processes of building construction. Thus, the process modules can be used as building blocks to assemble a composite process and interrelate it with corresponding building and construction information from the multi-model space. However, while such parameterisation is helpful, taken alone it only provides limited (re)usability and dynamicity.

Thus, the process modules are secondly enhanced with functional process-related knowledge that supports the retrieval and customisation of the process modules. Three kinds of knowledge are intended:

Application knowledge constitutes meta knowledge on the results and the contextual requirements of a process module. During module retrieval it provides for defining the construction task that a reference module must fulfil. In the following, it allows for the configuration of the module in regard to the actual context, e.g. specifying size and material of elements as well as available equipment and personnel. Furthermore, the features used to describe the applications of a module can be used to define module inheritance and classifications.

Compositional knowledge contains information about the coupling of the process modules into a logically consistent process. Defining the prerequisites of a module to execute and the outcome generated by a particular task it allows for the formal interconnection of the modules as well as for the identification of the constraints in regard to the already preselected modules.

Strategic knowledge contributes construction management heuristics and planning rules to support pre-configuration and composition of process modules. It is applied to deduce subordinate process modules by explicating subprocesses of higher level process modules taking in consideration project constraints represented in the domain models and/or general cross-model rules.

Overall the utilisation of the application, composition and strategic knowledge for the retrieval and customisation of reference modules relies on the access to model-based information on the anticipated construction results and the corresponding production context in the multi-models. This underpins the role of the model framework for the process-centred harmonisation and interlinking of the distributed information resources on the building, the construction site facilities and equipments, the project organisations and the related construction management plans.

4.2 *Reference modules for construction process configuration*

Figure 4 illustrates the application of reference process modules and the utilisation of knowledge extensions in the proposed modelling approach.

The main tasks of construction process modelling is the detailing of a given construction schedule or superordinate construction process model. To semi-automatically retrieve and customize the necessary sub-processes it should already provide interrelations to elements within the involved multi-models.

For a given modelling task, a three step approach may be followed. In a first step the applicable reference modules are retrieved from a catalogue and loaded into the process configurator. In a second step these modules are instantiated through reasoning about the configuration and compositional knowledge to interlink them with adjacent modules in the process network and provide them with the necessary resource information from the domain models. In particular, using the compositional knowledge process consistency is evaluated and validated. At last, in a third step the pre-configured processes within the process modules may be explicated and expanded to subordinate subprocesses by applying process strategies retrieved from the set of available strategic knowledge modules and combining these with additional information retrieved from the domain models.

4.3 *Generation of simulation models*

The configured construction process models can on the one hand be used to visualise, coordinate and monitor construction execution. On the other hand they can enable the creation of subsequent simulation models for the validation and optimisation of the execution plans.

Typically, such simulations include event-based logistics and construction/assembly tasks, e.g. to find out best supply chain alternatives, storage place locations and size, crane numbers and positioning. On large construction sites such simulations require complex modelling and information acquisition that are currently mostly done from scratch. The process is performed by highly specialised personnel and may take weeks to months to complete. Thus, whilst indisputably useful, simulations are only rarely used in current practice, due to the time problem.

With the proposed multi-model framework the situation can be greatly improved because most of the information required for a simulation model is actually available in some form in the model space and can be identified and extracted via appropriate basic model services. Moreover, the integrated Construction Process Model can be parameterised and used as reference task that can be easily instantiated in a respectively defined workflow.

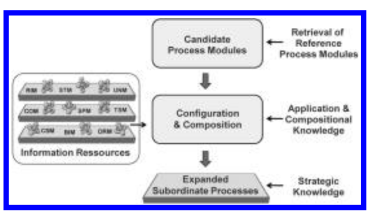

Figure 4. Principal approach to the modelling of construction processes.

Figure 5 illustrates the principal approach to generate and run simulation models in Mefisto. Based on the interlinked construction process model the process-related components of the simulation model are defined to explicitly represent particular construction production, logistics and erection tasks within the simulation environment. One of the main research targets in the Mefisto project is the development of methods for the derivation of such *Simulation Modules* from the processes and their underlying reference process modules.
The construction process model also identifies static simulation components. Depending on the simulation goal such components may include the equipment, the site facilities and the materials from the construction site model as well as the building elements from the building information model and qualitative, temporal and monetary qualities from the respective construction management models. If necessary, complementary information on the static components can be pulled up from the multi-model space via the dedicated interoperability services. Ideally, data acquisition may be performed semi-automatically (using filtering and mapping) whereas model formalisation and populating the model with data can be facilitated by dedicated tools or services taking into account the involved model schemas.

Finally, simulation results can be used to provide feedback to the superordinate process models as synthesised input to higher level model representations, e.g. as performance indicators, summarised time/cost values etc. Hence, simulations can not only prove planning alternatives but can also serve as basis for higher level decision making and risk assessment.

5 CONCLUSIONS

In this paper we described the main concepts of a new ICT approach to construction management enabling stronger integration of clients and constructors and achieved with the help of an open information management platform and a set of interoperable models and services linked together by a collaboration ontology. The developed classification system for processes, models and services provides useful guidance for similar further developments as well

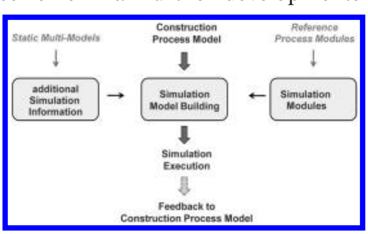

Figure 5. Principal approach to modelling and using construction simulations.

as clear implementation targets. Beside improved integration, considerable benefits of the approach are expected in the achievement of faster, more accurate and more efficient simulations, prognoses and project decisions. The status of the research is in the end phase of conceptual development. Based on the outlined specifications several components are preliminary prototyped.

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ICT-supported end user participation in creative and innovative building design

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ABSTRACT: In this paper we describe an ICT-supported method, VIC-MET, to support innovative and creative end user participation in the building design process. We also describe the actual process used in the development of VIC-MET. The method was developed in cooperation between university and two major engineering and architectural companies. Experiences from design of the two companies' new headquarters were used as input to method development and they have as well provided cases for method evaluations. The method supports user involvement in every phase of the design and construction process and with an individual setup depending on design context. VIC-MET has validated the need for enhanced methods to involve end-users of buildings in a collaborative/participative, creative and innovative building design process. The industry partners also appreciate the development, enhancement and extension of existing methods for user involvement in the building process.

1 INTRODUCTION

The latest decades of advances within Information and Communication Technologies (ICT) have paved the way for development of effective, efficient, and user-friendly building process support systems. We recognize introduction of object oriented parametric data modelling systems to house building models and advances in the Human Computer Interaction (HCI) domain to support collaboration and access to Building Information Modelling (BIM) models. The prerequisites for establishing a design environment, where early decisions and needs capture together with building end-users are at hand. We should now be able to put greater focus on optimisation of functional building systems, prioritization needs, requirements on the component building systems and evaluations of proposed solutions. In this paper we describe an ICT-supported method, VIC-MET, to support innovative and creative end user participation in the building design process. VIC-MET is a general method for user involvement in every phase of the construction process supporting an individual setup for each type of usage.

2 BACKGROUND

2.1 *User driven innovation*

If we do a Google search on the text "user-driven innovation" we achieve 1.8 million hits and with "innovation" 107 million hits.

There is a long list of methods and models, which can be said to support user driven innovation, see also (Von Hippel 2005), Beyer & Holtzblatt 1998), (Gero & Maher 1993), (Rogers 2003), Pittaway et al. 2004), and (Brandt et al. 2005).

A central issue in involving users is to uncover both known and not yet recognized user/client needs on functionality and form of new or refurbished buildings.

We here describe user driven innovation as a 'systematic approach to develop new products and services, building on investigation or adoption of users life, identity, praxis, and needs including unrevealed needs' (Christiansson et al. 2008).

2.2 *Participants*

The project User Involvement in Construction—Virtual Innovation in Construction, VIC, is financed by the Danish Enterprise and Construction Authority and the Programme for User Driven Innovation. It started August 2007 and finishes in June 2010. Project participants are two major engineering and architecture companies in Denmark, Arkitema Architects and Ramboll A/S, together with Aalborg University, Department of Civil Engineering.

2.3 *Project goal*

The project goal is to create an ICT supported methodology VIC-MET to involve building end user in a creative innovation process together with building designers, to capture and formulate end-user needs and requirements on buildings and their functionality.

3 THE VIC METHODOLOGY

3.1 *Development of VIC-MET*

The VIC method (VIC-MET) was itself developed in an innovative/creative design process. The Contextual Design method (Beyer & Holtzblatt 1998) has given inspiration in the development of the VIC method.

The Confluence 'enterprise wiki' from Atlassian, http://www.atlassian.com/, was chosen to serve as a hosted project web also housing the VIC Public Space. VIC Confluence was mainly used as a dynamic content management system and also used to take real time notes during physical and virtual meetings.

3.2 *VIC-MET spaces*

The method supports user involvement in every phase of the construction process and with a unique setup depending on design context. Four spaces to support the innovative/creative design process are defined; The Contextual Inquiry Space, the Conceptual Modelling and Game Space, the Functional Building Systems and Consolidation Space, and the Solution Space. See Figure 1.

3.3 *Using VIC-MET*

The end-users can be more or less involved in the design. In VIC-MET we differentiate between User Involvement and Co-Creation. In the first case the users are typically presented alternative solutions to comment on and in the latter case they are deeply involved in the design activities.

The following activities in VIC-MET spaces can be distinguished:

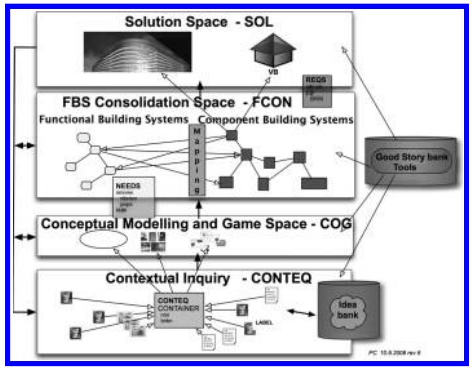

Figure 1. The four design spaces in the Virtual Innovation in design Method, VIC-MET. From (Christiansson et al. 2009a).

Activities in the *Contextual Inquiry* space (CONTEQ)

- Formulate Design/Innovation domain.
- Set up design team including proper end-users groups.
- Plan the whole design process.
- Identify/allocate resources such as Idea bank, Best practice, Contextual Inquiry Bank.
- Allocate tools from the ICT Tools Bank.
- Perform contextual inquiry including needs capture.

Activities in the *Conceptual Modelling and Gaming* space (COG)

- Develop conceptual models (e.g. using Contextual design methodology).
- Needs listing.
- Common values development.
- Functional Building Systems specification.
- Creative/Innovative design.
- Allocate tools from the ICT tools bank.

Activities in the *Functional Building Systems Consolidation* space (FCON)

- Needs consolidation, weighing and listing.
- Project vision formulation.
- Prioritizing needs.
- Mapping of Functional Building Systems (FBS) and Component Building Systems (CBS).
- Listing of requirements on Component Building systems.
- Component Building System modelling.
- Allocate tools from the ICT tools bank.

Activities in the *Solution* space (SOL)

- 3D virtual building modelling of (alternative) solutions.
- End user evaluation of solutions.
- Documentation of end user feed-back.

– Allocate tools from the ICT tools bank.
– Choose solution(s) or return to the FCON, COG or CONTEQ space.

3.4 *The VIC-MET tools box*

Many different ICT tools can support the VIC-MET activities described above. In the VIC-MET book (in Danish) the tools are categorized according to the ontology below:

Data collection and modelling
- Interviews and user investigations.
- Conceptual modelling.
- Scanning and surveying.
- 3D modelling.
- Registering and measurements.
- Analyses and prioritizing.

Communication and collaboration
- Communication.
- Information and knowledge sharing.
- Relationship and competence handling.

Visualization and interaction
- Still renderings.
- Animation.
- Interactive visualization.
- Virtual reality.
- Virtual 3D communities.
- Rapid prototyping.

Examples of tools within each main category are e.g. IHMC CmapTools for conceptual modelling (Novak et. Al, 2006), Atlassian Confluence for web-based collaboration, information and knowledge sharing, and Ramboll VR Wii for interactive visualization.

4 CASES FOR EVALUATION

VIC-MET was developed in parallel with design and construction of the new Ramboll Head Office (RHO) and the new Arkitema office (Mikado House), both situated in Copenhagen, Denmark. The RHO and Mikado House cases have contributed in assembling experiences input to the development of VIC-MET and served as a test bed for VIC-MET.

4.1 *The Ramboll Head Office case*

Three test cases were carried through in the RHO case.

1. Color selection
2. Placement of reception desk
3. Interiors of meeting spaces.

The end users involved in the process came from the interior and identity groups. The user participation was mainly of type User Involvement rather than Co-creation. The user took standings on principles of color distribution and range in the building, as well as general views on the artists color composition.

The following conclusions were drawn from the color selection case. The interior color selection process requires models on appropriate detailing level. In this case the artist found the original digital model too detailed to work with. It is also very important to do a proper calibration of the displays used in the coloring and evaluation process and keep in mind that lighting conditions in the model greatly influences the impressions.

In the 3D model the users could experience the size of the colored areas, distance color visibility, and color compositions. The first evaluation on high level took place in the Solution (SOL) space and the feed-back was introduced by the artist in the subsequent return to the Conceptual Modelling and Game (COG) space. Here the end users agreed on for example nice and ugly coloring, correlation with the personality of the building, and the amount of complement colors and contrasts. The user needs and views were included in a not very formal way to the FBSs and via color attributes of components in the CBSs, which were later realized in new solutions in the SOL space. See also Figure 2.

Another Rambøll case was—placement of reception in the entrance hall. The activities in the Contextual Inquiry (CONTEQ) space, invoked mainly the executive level in Rambøll. These end users expressed a lot of needs and requirements with at first glance contradictory functional and visual challenges. Four initial proposals were presented for the end-users in the solution (SOL) space, to support the following discussions in the Conceptual Modelling and Gaming (COG) space. It was for example discovered that there

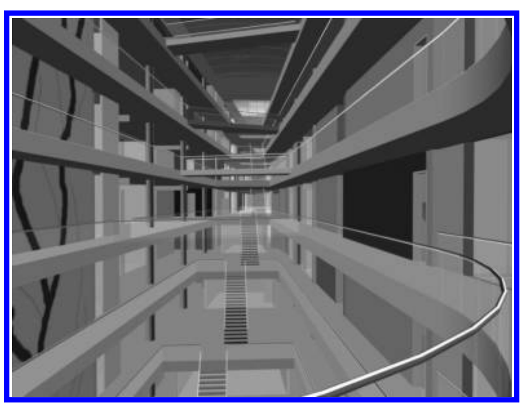

Figure 2. Coloring the new Ramboll Head Office.

were different requirements on placement of the reception depending on if it was watched from the entrance or from the inside of the entrance hall.

The function of the reception related to today and future expected functionality was further discussed in the Functional Building Systems Consolidation (FCON) space. Revised solutions were evaluated and discussed in the SOL space. See also Figures 3–4.

A special VR-Wii solution was developed at Rambøll providing the users a simple and cost efficient way to navigate in the virtual buildings solutions in the SOL space. See Figure 5.

A particular user group was early established to take care of end user needs in connection with interiors and facilities in meeting spaces and common locations. In this case VIC-MET was used late in the process involving a choice of specific furniture and their placements. Solutions were presented in both virtual and real settings in the existing office. The main activities took place in the FCON and SOL spaces. Special regards to possibilities for housing both social and more private meetings were studied in the café space. See Figure 6.

4.2 *The Arkitema headquarter case*

The Arkitema office project started in 2005. The kick-off procedure and early workshops from this work gave fruitful input to the VIC-MET development. An intentional focus in the office design was to keep the design activities on a high abstraction level with focus on common values, needs and functional building performance. User involvement procedures for the VIC-MET were set-up and evaluated for the office space design case.

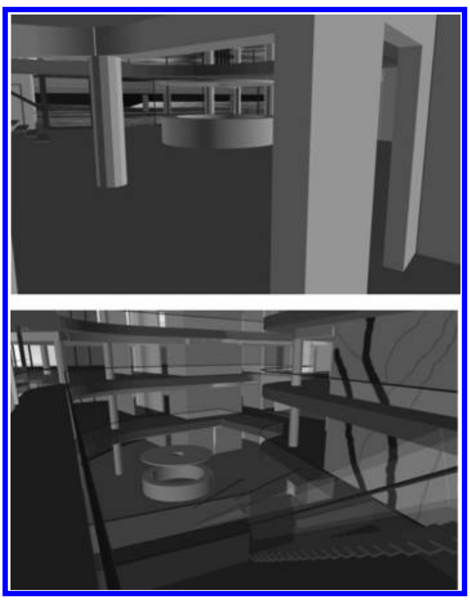

Figure 3. Entrance alternative 1 in the new Ramboll Head Office.

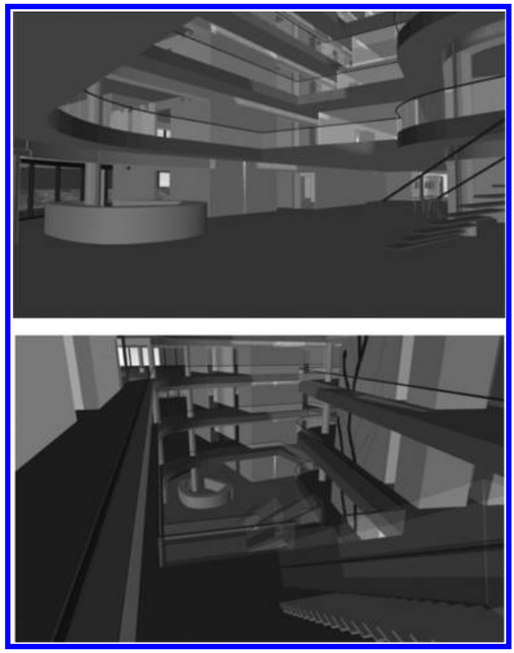

Figure 4. Entrance alternative 2 in the new Ramboll Head Office.

Figure 5. A special VR-Wii solution was developed at Ramboll.

Figure 6. The combined café and meeting space at the new Ramboll Head Office.

Figure 7. Video documentation of design, evaluation activities in the SOL space at the Panorama VRMediaLab Aalborg University.

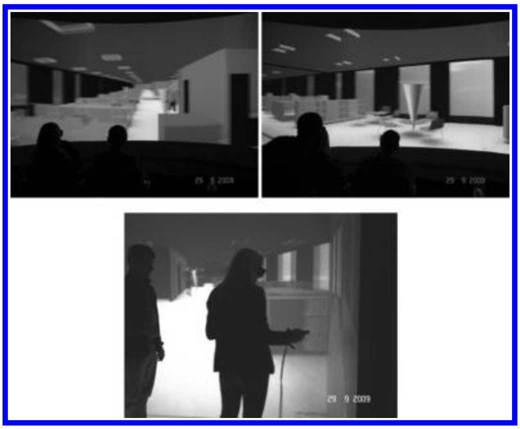

Figure 8. Use of symbols in the virtual building office space to evaluate placements of privileged meeting places in the Panorama respectively Cave at the Aalborg University.

Alternative solutions were partly changed and evaluated in the Panorama and Cave at the VRMediaLab at Aalborg University. It was concluded that it was feasible to make real time changes, annotations, and to store different solutions. It was also concluded that is very important to work on a uniform abstraction level, dependent on design context and user skills. See Figures 7–8.

4.3 *Late Brain Injury Center case*

Finally VIC-MET was assessed in connection with design of a Late Brain Injury Center including patient housing, training facilities and Living Lab facilities for Aalborg University. See Figure 9. In this case the architect for a first alternative presentation compiled the end users needs and wishes. The architect leads the walk-through for a broad (15 persons) end-user representation of clients, patient relatives, AE design team, nurses, and university Living Lab researchers. Feed-back from evaluations in the SOL space were used as input to the architect for further iteration and alternative evaluations.

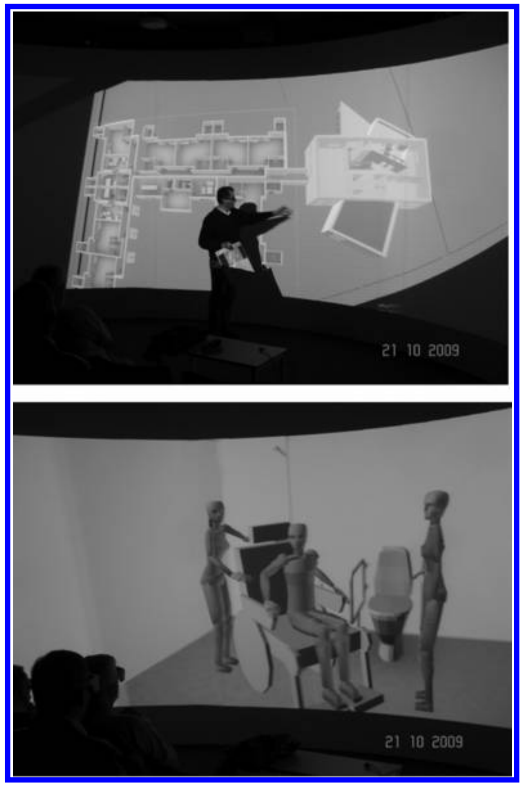

Figure 9. User Involvement in the design of The Late Brain Injury Center Frederikshavn Denmark. VIC-MET development support.

5 CONCLUSIONS

The VIC-MET was developed to support user participation in innovative and creative building design. The method supports user involvement in every phase of the construction process and with a unique setup depending on design context.

VIC-MET has validated the need for enhanced methods to involve end-users in a collaborative/participative creative and innovative building design process. The industry partners also appreciate the development, enhancement and extension of existing methods for user involvement in the building process.

The VIC-MET will support a future more performance based design process and development of ontologies to better describe functional building systems. See also (Christianson et al. 2009b).

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Compatibility between FIDE data model and ISO 10303-236

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ABSTRACT: The use of data models in the construction and furniture industries has become more common. The exchange and integration of information among different stakeholders who participate in building and interior design projects are very important to improve the efficiency and reduce time and economical costs. To ensure the interoperability between a building project and its interior design will provide agents with a very powerful tool to make design processes more dynamic and efficient. FunFide initiative focuses on the convergence of FIDE data model and the standard ISO 10303-236, also called AP236 or funStep.

1 INTRODUCTION

The construction and furniture sectors are closely related in the building area. Therefore, agents of different industry areas participate in the same building project and exchange a lot of information. In this way, some agents have to adapt their designs to requirements of other agents.

Each company and/or participant in the building project uses tools or applications that suit its needs: structural analysis, facilities calculations, design, cost control and management applications, etc. But, in most cases, these applications are not compliant with others software tools. This is an important problem for Public Administrations that require a large amount of documents and information to verify the compliance of the building project with a specific normative.

Information and Communication Technologies (ICT) will provide the necessary potential to achieve cost reduction in the companies and to improve design processes and logistic production. Manufactures, material suppliers and distributors will be able to exchange commercial documents in standardized formats and catalogues. This will facilitate the product information management along its life cycle.

The ICT potential will increase with the use of standards and information models, making easier the exchange information among the stakeholders both of the same industrial sector and related sectors, and decreasing the resources of all involved agents of a project. This specially applies for the Public Administrations in their task of the management and control of the information, documents and files generated during the construction process. In this way, they can optimize administrative processes that consume a big amount of resources as a result of an inefficient management of the information exchange.

The main aim of this paper is to describe the integration process between the standard ISO 10303-236 [1], called funStep [2], and the FIDE data model [3]. FunStep is a standard for the exchange of product catalogues information and FIDE data model is used for the exchange of construction project information. The integration between these standards will allow putting together all the information relating to a construction project. This information will be necessary to validate the safety, habitability and functionality requirements.

2 OBJECTIVES

The main aim of this project is to analyze the convergence between the standard of furniture industry (funStep) and data model of building sector in Spain (FIDE).

It is important to develop a common nomenclature, so that computer systems will understand when they are exchanging information.

It is necessary verify the compliance of a building project with normative and rules related with building elements, with special distribution and with furniture and their catalogue specifications. The integration of the two main standards in a building project will provide an important advantage to Public Administrations that should process all of these documents and guarantee the compliance of the project with the laws.

To sum up, the objectives of the project can be enumerated as follows:

– To promote the use of information technologies in traditional sectors as furniture and building industries that normally are made up of small

and medium companies. These companies will increase their productivity by means of the efficiency of their communications.
- To facilitate the common analysis of construction and interior design projects, to make it possible to verify different rules (for example, normative for the accessibility in public buildings) in a more efficient and real way.
- To facilitate the interoperability between the sector stakeholders independently of the computer applications used for different purposes.

3 FIDE INITIATIVE

In this section, some fundamental concepts of FIDE initiative will be described. These concepts will help to understand the data model structure and the necessity of the compatibility with other standards.

3.1 *Data model architecture*

FIDE model has specially been developed in the area of quality management in the construction sector. In the case of the Spanish situation the quality control procedures are mainly driven by de Administration (control book, quality profile, building book, etc.). The safety and habitability requirements of buildings set out in the Spanish Technical Building Code [4] have also been analyzed. Thus, FIDE data model includes all the information, both structural as administrative, related with a building project.

The basic data model structure is defined as follows:

- Each entity represents a real world concept. These elements are represented by means of XML schemas and have a set of fields for identification, description, location and specific characteristics and relations with other elements.
- There is a mandatory element called *DescriptorEdificacion*. It contains general data of the construction project and structural information about the building.
- There are several fields called *Collections* where similar elements will be put together to establish conceptual groups (building elements, materials, agents …)
- The whole structure is a layered structure:
  - Each layer contains the entities that several entities from an upper layer do use. This way the model avoids duplicity of re-used elements in the model.
  - The lower level is called kernel. It contains the most basic and re-used elements.

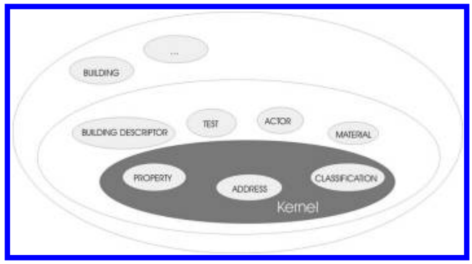

Figure 1. FIDE general structure. The structure is layered.

3.2 *Technical issues*

FIDE data model has been developed with XML technologies. The reasons for adopting these technologies are varied. First, XML meta-language is the de facto standard for the data exchange in the network. This will facilitate the relation between the Administration and the industry. Besides, there are a lot of available software tools to work with XML, a lot of tools for the manipulation of XML files and a lot of development tools such as programming libraries and SDKs (Software Development Kits). This does easier the adoption in the industry of the XML structures. Finally, there exists a set of XML-based technologies to manipulate XML files: XSL, XSLT, XPath and XQuery, etc, which will facilitate the FIDE files transformation.

Moreover, the most extended international standards in this sector, ISO STEP and IAI IFC [5], evolve or already support XML.

4 ISO 10303-236

In this section, some details about the international standard ISO 10303-236 (called AP236 or funStep) will be described.

ISO 10303-236 is the international standard for the information exchange in the furniture industry and wood product manufacturers. This standard focuses on the needs of the sector related to the communication between different computer systems. FunStep allows defining parameters furniture design and catalogue, decoration and interior design information.

The standard deals with information relating to the variability that is possible in a piece of furniture or a wood building element. Scopes of funStep standard are the following ones:

- Product libraries.
- Catalogue structure.
- Furniture specifications (colour, materials, etc.).
- Furniture properties (price, dimensions, etc.).
- Product variability.
- Interior design projects.

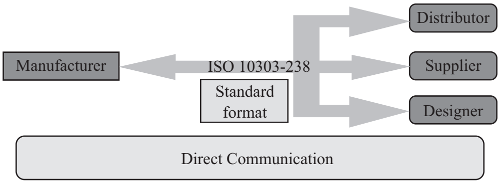

Figure 2. Exchange of information among different agents.

FunStep standard has been developed with XML technologies, following ISO 10303-28 recommendation.

5 CONVERGENCE ANALYSIS BETWEEN FIDE AND FUNSTEP

To perform the integration between FIDE and funStep, the following steps have been developed. First of all, it was necessary to identify application scopes of each standard and define common use cases. After this, it was necessary to define common points where it will be possible to introduce information from other data model, without modifying the consistency and the validity of the information contained in the first data model. Finally, it was necessary to identify semantically similar elements and elements with an ambiguous meaning in the different application scopes and convergence use cases. In addiction to the elements, it was necessary to consider the existing constraints in both data models and to plan the convergence strategy.

5.1 *Application scopes*

The first step to approach the funStep and FIDE convergence is the identification of different standard scopes, their common issues and their divergences. In this way, a map of common scopes that will be the starting point to deal with convergence tasks is obtained.

First, FIDE application scopes were analyzed. The development of this format is based on the analysis of different mechanism used by Spanish Public Administrations at regional and national level. At regional level, FIDE includes information related to the Housing and Buildings Quality Plan. Thus, software applications, such as Quality Profile have been developed to the promotion and advancement of quality in the building sector. Other software applications are Building Book, which includes the administrative and legal documentation, technical documentation and documentation concerning the use and maintenance of the building. At national level, FIDE includes information of the different Basic Documents which are contained in the TBC (structural analysis, thermal and energetic analysis, acoustical scope, fire protecting scope, etc.). Thus, it is possible to save in a FIDE format file the building information related to these issues.

Other hand, it has been analysed application scope of AP236 standard. By means of this standard, it is possible to exchange simple and modular product libraries, their specifications, properties, configuration and geometry, as well as interior design projects.

5.2 *Convergence use cases*

After analyzing the information of the application scopes of both standards, FIDE and funStep, it was necessary to establish a set of real situations or use cases where the convergence between both standards is important to obtain complete results. Some scenarios are proposed to highlight the need of the integration of the information:

- *Integration of furniture in a building project:* Architects and interior designers share the information of a building project in order to import products of different manufacturers and to decorate rooms established by the architect. The more important information in this use case is the building elements, spaces and furniture dimensions and geometry.
- *Fire safety validation:* Building elements, furniture, etc., have to fulfil a set of minimum requirements related with the fire interior spread (integrity, isolation and durability), evacuation (dimensions of ramps, stairs and doors, etc.), and fire resistance.
- *Building use safety validation:* Building elements have to be designed to minimize risks associated with the use of the building. In this scenario it is necessary to take into account properties of ramps, stairs, doors and other elements which are near them.
- *Cost calculation:* The construction of public audience buildings needs to calculate its costs more accurately, including the furniture. In addiction, taking into account the specific

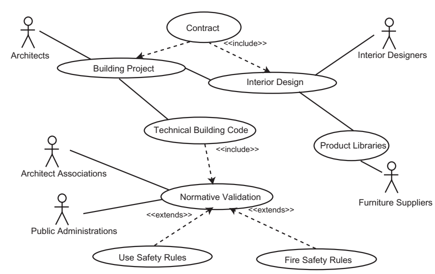

Figure 3. Relations between use cases and application scopes for the integration between funStep and FIDE.

requirements of these building, it is necessary to evaluate the complete project. Accessibility rules or fire safety normative take into account building elements like stairs, doors as well as furniture dimensions and location.

As a summary of case uses defined previously, a general scenario is shown in the figure. In this scenario, it is possible to identify the relations between the previous use cases and the application scopes for the integration between funStep and FIDE.

Following, the fire safety validation use case will be described with more detail.

5.2.1 *Fire safety validation use case*

The Technical Building Code includes a Basic Document based on fire safety. It describes fire safety requirements that must be fulfilled by a building and its elements. The document focuses on the following scopes:

– *Fire interior spread:* It is necessary to divide the building in fire areas in order to guarantee the fire safety. In this way, some elements should have special properties. For example: Access doors should have integrity, isolation and durability features.
– *User evacuation:* It is necessary to calculate the dimensions of the evacuation path (the width of ramps and doors, the useful area of stairs, etc). For example, the maximum number of users that can go down a stair in an emergency case determines its width.
– Fire resistance of structure elements.

In this case use, involved agents are architects, architect associations, door, stair and wood structure manufacturers. These agents will use the following computer applications: design applications, building elements catalogues, applications for the normative validation, etc.

The use case information flow starts with architects. Firstly, the architects will draw the building projects and select doors and other wood elements from a commercial product library. Architects will be able to know the product specifications, like, for example, fire rating, thermal transmittance, etc. in real-time. Thus, they will select the best product in order to fulfil the national fire safety requirements.

Public Administration will review building projects and verify their compliance with fire safety normative.

5.3 *Convergence points and semantic analysis*

Use cases allow identifying elements that require information from both standards. These elements are the starting point for the model integration. When the identification of these concepts was done, it was necessary to perform a semantic analysis of data.

Elements involved in use cases defined previously need to be analyzed semantically. This analysis consists of establishing the meaning of these elements in order to guarantee that they refer to the same concept in both standards.

In this way, the semantic analysis includes types of elements, dimensional properties, and fire performance. For example, it is important to check if "type of door" has the same meaning in FIDE and in funStep. Both standards define a door depending on its opening system, so the result is positive.

5.4 *Convergence roadmap*

After the identification of common points between the standards, it is necessary establish a list of tasks to perform the integration of the two formats. These tasks will be proposed for some use cases.

Thus, the roadmap will be based on the development of software applications that resolve the problems described in case uses. First, it will be necessary to update or adapt both FIDE and funStep. After, the software application will be developed. This application will be able to read FIDE compliant files and funStep documents and to put together both building and furniture and wood products information. Finally, a user guide will be developed to explain different ways for the integration and exchange of FIDE and funStep information. This guide will help software developers to facilitate the interoperability between their applications.

6 CONCLUSIONS

Following the most important conclusions are shown:

– The use and implementation of data models involve the need for mechanisms to integrate different data in software applications.
– Architects and interior designers will have complete projects available to estimate costs in a more efficient ways. Also, they will be able to guarantee the compliance of their projects with a normative, and, finally, they will be able to update their product libraries in real time.
– The integration of the information will facilitate the tasks of technicians who have to evaluate the fulfilment of building projects.
– funFIDE initiative will establish the connections between construction and furniture industries by means of FIDE data model and funStep standard.

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[3] www.fide.org.es
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A framework for multi-model collaboration and visualisation

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ABSTRACT: Information in construction processes is represented by various independent information models. Hence, the management of the resultant multi-model space is a very important issue for large scale construction processes. However, automated multi-model interoperability is still poorly supported by ICT. In this paper, a new framework for the integration of model collaboration and visualisation tools is proposed, as enabler for further research and development work in the area of model-based construction information management. The framework is implemented as a lean set of Eclipse plug-ins, each providing its own functionality. These plug-ins may have interdependencies to allow clients to reuse them. Consequently plug-ins can be information consumers and providers at the same time. The framework offers an extensible data model for a multi-model project, whereby plug-ins can take part in the global load-edit-save cycle.

1 INTRODUCTION

The large German BMBF research project Mefisto inaugurated in spring 2009 with duration of three years aims at overcoming client-contractor interoperability problems in construction processes based on partnership (Scherer et al. 2010). One of the project's main challenges is the management of the *distributed multi-model-space* defined via model schemas for building information, construction site and equipment information, costs, specifications, time schedules, organisation, processes, risks and uncertainties. The instances of these model schemas, i.e. the actual model data, need to be transformed, exchanged and managed horizontally (between client and contractor and among various discipline-specific representations), longitudinally (in their temporal development along the project phases) and vertically (on different levels of abstraction, to support different levels of decision making). An overview of these model assignments can be found in (Schapke et al. 2010).

The AEC community has developed IFC as a powerful extensible building information model which is increasingly gaining practical importance (Kiviniemi et al. 2008). However IFC does not (and is not intended to) store and carry all relevant data for all multi-faceted construction processes. Hence, nD modelling problems occur that are inherent to construction (cf. Aouad et al. 2007). There are approaches to extend IFC in order to cover more building process related information, as shown e.g. by Froese (2003), but such solutions have various limitations and assume IFC-conforming tools in all construction subdomains and subtasks, which is not the case in current design, construction planning and management software.

Therefore, based on the fact that not all relevant data can be structured in a single super schema, our approach is to take existing models as they are and treat them as one *interoperable multi-model space*. Advantages of that approach are as follows:

1. Existing and accepted data models like IFC or the German GAEB specifications model can be used further without modification;
2. According to a given task or process, information can be assembled in a straightforward way by composing relevant model data;
3. IT coverage of building process information can be extended by alternative data models, as suggested e.g. by Keilholz et al. (2009), or by data models created in future.

This shifts the paradigm from BIM-centred information management to a *federation of coequal multi-models* (Figure 1). The challenge is to give

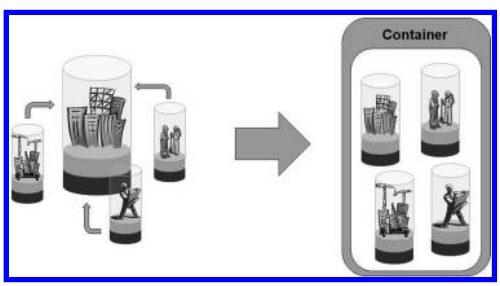


Figure 1. Paradigm shift from a BIM-centred approach (left) to a federation of coequal multi-models (right).

information access to a consumer (a person or software) as it would be by a single schema. This implies automated collaboration of the participating single models which is still poorly supported by current IT.

In this paper we present the main concepts and features of a novel framework for multi-model collaboration and visualisation, developed with the goal to facilitate further research and development of multi-model management tools such as:

– Multi-model filtering
– Multi-model checking
– Multi-model mapping
– BIM-based and topological (network-like) multi-model visualisation
– Collision detection
– Process simulation.

2 THE MULTI-MODEL CHALLENGE

Consistent information access to the multi-model space is the key for general multi-model acceptance. In this chapter, the issues which drive the achievement of this goal are discussed.

2.1 *Filtering*

Current model filters should be extended to multi-model filters to allow combining selection criteria from the separate models. In analogy to geometry, domain specific collision detection can validate multi-model data, e.g. time checks, cost limits or personal responsibilities and any combination of them. A special aspect is versioning where two single model instances of the same real world object represent different states in the multi-model space. Compare methods can help to find and reproduce the changes between such states. This concept can even be extended up to versioning of multi-model instances.

2.2 *Visualisation*

Visualisation is used to present information in a context relevant way, appropriate for the actual supported process. Here the focus of work is on creating corresponding information views in relevance to very different visualisation technologies. This is in close relationship with the next addressed issue.

2.3 *Data access*

Since wee assume no common schema, neither explicit (as a formalised model) nor implicit (as a query interface), various basic questions arise:

1. What is the representation of a multi-model and how are the single-models accessed?
2. How are associations between the single-models established?
3. How can the combined information be accessed in a generic way?

These questions are subject of ongoing research, but there are just concepts and no comprehensive answers as yet.

2.4 *Representation*

In principle, the approach for multi-model information representation using a federation of coequal models can be based on so called *information containers*. Such containers can hold the single model data either by a URI reference to the physical document or data repository, or as embedded data. Given a XML serialisation, a corresponding link-element, respectively a CDATA section, can be used. Besides, some metadata must be carried for superior information process data and quality information about the single models. This metadata is not intended to provide multi-model collaboration by itself but can support that process by its context data.

Associations between the participating single-models are a key aspect of multi-model collaboration. Ideally, every real world object representation in a multi-model must be allocated to its different single model representations. Therefore semantically equivalent concepts in a model pair must be identified and have to be connected. While manual processes for that purpose are already established e.g. in standard cost calculation software, development of automatic *matching strategies* are one of the significant challenges in multi-model research. Matching may also imply various data transformations (mappings) that need to be taken into account.

2.5 *Query language*

To enable generic access of multi-model data, a common query language has to be defined. However, without the availability of a common schema this is very difficult to realise. Knowledge about structure and attributes of each single model and about their associations is necessary. A basic approach here can be to shift the responsibility for semantic concept matching to the query creator, in similarity to SQL where relation joins have to be defined at query level. Nevertheless, in order to avoid redundant manual or semi-automated matching strategies at query runtime, the association process should be performed before that point. Therefore, once made, associations between single models have to be kept accessible so that they can be quickly invoked on query execution. Consequently, such associations should have a serialisation. Thus, they can be embedded in the multi-model container to ensure multi-model consistency.

3 PROPOSED FRAMEWORK ARCHITECTURE

In this chapter we present the details of a proposed new software framework that helps for the solution of the outlined multi-model challenge.

To begin with, the roles in the framework lifecycle have to be defined. Accordingly, a person who develops the framework will be called *framework developer*, a person who uses the framework to develop a software product will be called *framework user* or *client*, and a person who uses the resulting product will be called *end user*.

The presented framework is intended to support the work of client developers and researchers on multi-model issues. Therefore its main *objectives* are to offer:

1. An extension mechanism to contribute the client software modules;
2. Modularity by itself and for the client modules to allow subset distributions;
3. A common user interface;
4. A possibility to load, hold and provide data of the single-model instances;
5. An implementation of the multi-model container format for persistence and data exchange.

Figure 2 provides an illustrative view of the overall concept, emphasising the idea of inter-connecting plugged-in clients and models in coherent manner with the help of the framework.

To comply with objectives 1 to 3, the Eclipse Rich Client Platform was chosen as runtime environment. Eclipse is built on Equinox, which is an open source implementation of the OSGi standard. As such it provides dynamic runtime modularity on top of a Java Virtual Machine (JVM). Software components, called bundles, can be run,

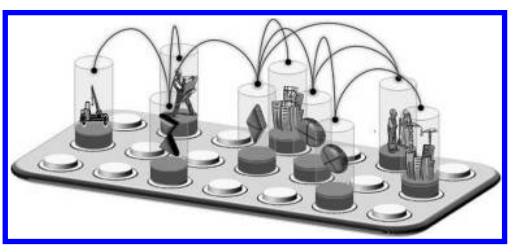


Figure 2. Overall concept of the proposed multi-model framework enabling development of interoperable plug-in clients.

stopped and updated without halting the JVM. In that way it is possible to deliver the framework, its libraries and a yet unknown amount of client components in a straight-forward manner. Bundles describe their interdependencies in a manifest file, which allows a fine grained composing of runtime artefacts—as it is necessary for building subset distributions of the framework and client modules by framework users (D'Anjou et al. 2006).

Eclipse follows a *plug-in concept* by providing a generic extension mechanism via XML-descriptors. Plug-ins may offer extensibility by extension points and can contribute additional functionality by registration to other extension points. Due to the use of XML-descriptors, Eclipse can defer plug-in activation to the point where Java classes have to be loaded from it. This so called lazy loading allows a fast startup sequence and a small memory footprint, which is necessary when working with huge data models like IFC. Therefore, framework components and client modules are implemented as Eclipse plug-ins.

Furthermore Eclipse comes with the Standard Widget Toolkit (SWT), which is a Java library for the use of the operation system's native user interface elements. This enables a standard Look and Feel to the end user. An overview how to use Eclipse as an application platform can be found in (Gamma & Beck 2003).

Figure 3 below shows a screenshot of the graphical user interface of the developed multi-model

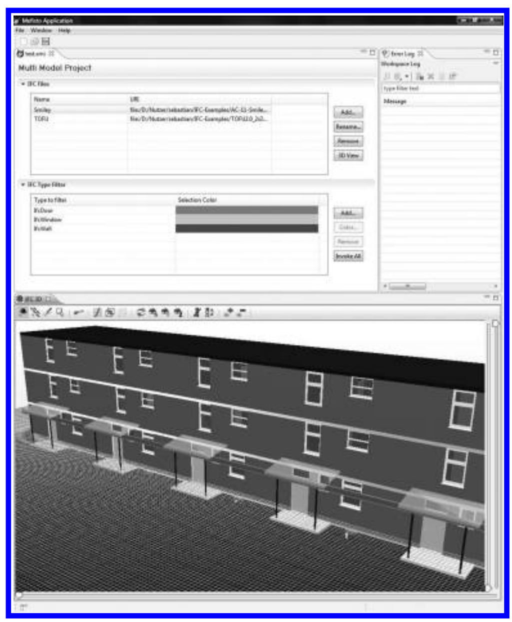


Figure 3. GUI of the framework with an example set of IFC related plug-ins.

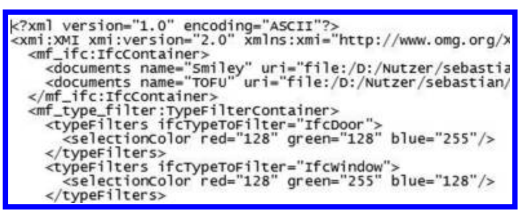
framework, with an example set of IFC related plug-ins. The top left editor part is dedicated to the functional representation of each client plug-in, e.g. loaded single-model instances. Further parts can be contributed by every plug-in, like the IFC 3D viewer which is shown in the bottom part.

In general, client modules are responsible for the resource management themselves. This means that they must provide a mechanism to load and manage instances of a certain single model on their own (objective 4). The framework already comes with plug-ins for managing IFC documents in SPF format (ISO 10303-21), GAEB-XML (GAEB 2009) and Microsoft Project XML (cf. http://msdn.microsoft.com/enus/library/). Support for further model types is planned. IFC-model support is provided by Open IFC Tools (OIT 2009). This is also used for the implemented IFC 3D viewer (cf. Theiler et al. 2009).

The framework defines an extensible data model for multi-model projects. Client plug-ins can provide their persistent data by implementing a *marker interface*. In this way they can take part in the framework's global load-edit-save cycle. The data can consist of single model instances, references to them and any data which is necessary to restore the state of a plug-in. Given that functionality, the data model of the framework can be seen as a universal container. Hence, it is a *multi-model container*, too (objective 5).

The framework expects persistent data to be created by the use of the Eclipse Modelling Framework (EMF). EMF is a toolset to produce source code out of structured models (Steinberg et al. 2009). It provides different serialisation mechanisms from which XMI was chosen for the framework's container persistence. Thus clients don't have to implement persistence themselves—instead they can rely on a consistent framework service.

Figure 4 shows a XML fragment of an example multi-model project's serialisation. The element *mf_ifc:IfcContainer* represents the persistent data of the plug-in which is responsible for holding IFC documents (e.g. as SPF or IfcXML files). The element contains a collection of such IFC documents that are relevant to the current project. They are stored by an URI-reference to their actual files. The element *mf_type_filter:TypeFilterContainer*



```
<?xml version="1.0" encoding="ASCII"?>
<xmi:XMI xmi:version="2.0" xmlns:xmi="http://www.omg.org/X
  <mf_ifc:IfcContainer>
    <documents name="Smiley" uri="file:/D:/Nutzer/sebastia
    <documents name="TOFU" uri="file:/D:/Nutzer/sebastian/
  </mf_ifc:IfcContainer>
  <mf_type_filter:TypeFilterContainer>
    <typeFilters ifcTypeToFilter="IfcDoor">
      <selectionColor red="128" green="128" blue="255"/>
    </typeFilters>
    <typeFilters ifcTypeToFilter="IfcWindow">
      <selectionColor red="128" green="255" blue="128"/>
    </typeFilters>
```

Figure 4. XMI serialisation fragment of an example multi-model project.

holds the data of an IFC-filter plug-in. In this case this is a collection of several filters for one IFC-type each and their dedicated selection color for the IFC 3D viewer.

4 PRINCIPAL FRAMEWORK USE

A client plug-in must be registered to the framework by a specifically provided *extension point*. It has to point to a class which implements the interface *IMfPlugin*. This type is the entry point for the data structure of the client plug-in. At runtime there will be one instance for each opened multi-model project. The interface signature is shown in Figure 5.

To explain the basic concept of the framework's use, the semantics of the four most important methods of the interface are shortly described below.

getPluginID()
This method will return a unique string (in the range of all client plug-ins), which is used to identify that client plug-in. Thereby, instances of further specific plug-ins can be found and accessed in the scope of the current multi-model project.

getDataClass()
If the plug-in offers persistent data, the method will return the concrete class which contains the entire data. This class must implement the marker interface *PluginDataRoot*. It is used by the framework to recognize the dedicated plug-in of a container's data element. The actual data can be accessed by calling *getData*().

init(…)
This method is called by the framework at the start of the plug-in's lifecycle. It is passed its context in form of the current multi-model project (*IProject*) and, if exists, the loaded persistent data of the last session. At the end of the lifecycle, e.g. at program exit, *dispose*() is called by the framework, where clients can release beforehand allocated resources.

createControls(…)
Due to the Eclipse lazy loading mechanism, a plug-in's user interface must not necessarily be rendered at the start of its lifecycle. Therefore this method is

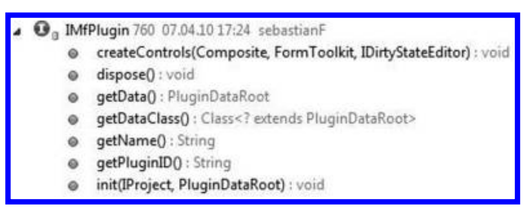


Figure 5. Signature of the *IMfPlugin* interface.

called when user interface controls are shown up first time. Clients can set up their user interface here, which is shown in the editor part inside a so called section. The name of the section is obtained by the method *getName*() and should represent the plug-in's name.

5 CLIENT EXTENSIONS

An important intention of the developed multi-model framework is to encourage clients to reuse and extend existing plug-ins. Thus, clients can make use of additional software libraries to achieve more efficient results. This means that a plug-in can be an information consumer and provider at the same time. Clients should respect that and provide their main functionality to others.

Plug-in implementers are free in their use of provided data, e.g. the end user selection of model instances in a table. In that way, a change management plug-in for IFC could interpret a single selected IFC document as basis for comparison against all other loaded ones, while it does not consume other provided models. On the other hand, a plug-in which links construction site data with time schedules automatically could just be able to make use of both loaded model instances. It would leave further instances unused, regardless of their selection state. However, client implementations should explain their behaviour and prerequisites to other clients and the end users in unambiguous way.

5.1 *IFC-based plug-in for multi-model filtering*

Figure 6 on the right presents an example of the IFC-based plug-in for multi-model filtering developed in the Mefisto project by extending and adapting the original tool described in (Theiler et al. 2009). It enables definition of filters on class and instance level, combined application and visualisation of multiple filters on multiple IFC and non IFC model instances, comparison of filters by means of multi-colour visualisation and so on. Moreover, via its integration in the proposed

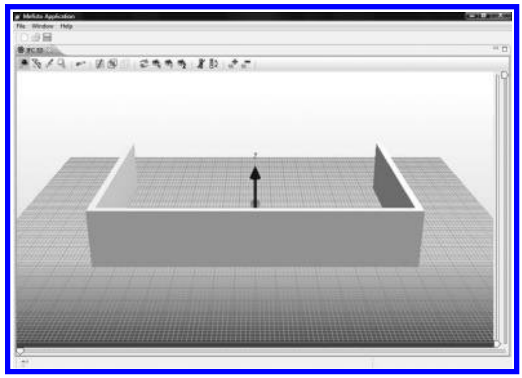


Figure 6. Screenshot of the IFC-based plug-in showing the result of a filter applied to the IFC model (walls, spaces) and a non IFC scheduling model (planned date of wall assembly).

Table 1. Client Plug-ins in the Mefisto project and the usage of their related single-models as input (In), output (Out) or both (I/O). Model processing shown in parenthesis is optional.

GRANID, RIB iTWO and Plant Simulation are commercially available tools that are being integrated in the Mefisto platform. GRANID is a management and controlling system developed by the project partner GIB Greiner GmbH, RIB iTWO is a new specification, cost calculation and scheduling system developed by the project partner RIB AG, and Plant Simulation is a widely known simulation tool of the Siemens AG.

Client Plug-Ins / Models	Process	BIM	Construction Site	Organisation	Specifications	Costs	Schedules	Risks & Uncertainties
Dynamic management of construction processes	I/O	(In)	(In)	(In)			Out	
Construction site configurator		In	Out	(In)		(In)		
Controlling and risk management	In	In		In	I/O	I/O	I/O	Out
Configuration and adaptation of simulation models	In	In	In	In		(In)	(In)	
Strategy and scenario manager for simulation tasks	In	In	I/O	In	I/O	(In)	(In)	(In)
Collision checker for supply and assembly tasks	In	In	In	(In)			(In)	
GRANID Plug-In	In	In			I/O	I/O	I/O	Out
RIB iTWO Plug-In	I/O	In		(In)	I/O	I/O	I/O	
Plant Simulation Plug-In	In	In	In	(In)		(In)	(In)	(In)

framework it can be used for a variety of purposes by other construction management services, such as scheduling, cost calculation and controlling.

5.2 *Further multi-model plug-ins*

Due to the genuine openness of the platform, various other single or multi-model plug-ins can be envisaged. In fact, using the described approach a number of such plug-ins is currently being developed or designed in the Mefisto project. Table 1 provides an overview of some of these client plug-ins and their related multi-model space.

Depending on the specific data and process context the actual information containers comprising filtered model instances of one, some or all of the shown models are assembled and passed to the requesting client plug-in and/or produced as output in uniform manner. Hence, while the underlying domain models can be quite different in structure, using the container approach and the basic framework functionality consistent multi-model interoperability can be achieved, provided that the required matching and mapping problems are adequately handled.

6 SUMMARY AND FUTURE PROSPECTS

The developed multi-model framework is seen as a relevant approach to foster ICT support for construction processes. It was developed as an extensible basis for upcoming multi-model investigations. Due to its predefined generic character, all functionality must be provided by client plug-ins. However, for convenience, various model management and visualisation plug-ins are built in. Necessarily, research must progress at least in the fields of single-model association and multi-model filters to better cope with the multi-model challenges in AEC/FM.

The framework has an implementation of a general multi-model container. This is seen as an elementary step and a precondition for further research in that direction.

The use of established frameworks like Eclipse and EMF and the developed design of a small and flexible extension interface enable clients to write plug-ins by less effort. Hence, developers can concentrate on conceptual work instead of developing test environments themselves.

Though the framework is already ready for use, further development is planned. Envisaged new features are metadata generation, web service support and ontology integration.

ACKNOWLEDGEMENTS

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Assessing commercial BIM software for dynamic building models

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ABSTRACT: Advances in building automation and increased attention to preserving natural resources challenges building operators to improve building performance while reducing resource consumption. Achieving this goal will require a dynamic building model capable of managing large amounts of instantaneous information and automating the control of building systems. Several commercially available Building Information Modelling (BIM) systems have properties that are well suited to serve as a platform for creating dynamic building models. This paper presents several benefits and limitations of utilizing a commercial Building Information Modelling (BIM) system as the basis for a dynamic building models. The authors highlight several specific examples from their experience and conclude with recommendations for overcoming the limitations of commercial BIM software to support dynamic building models.

1 INTRODUCTION

As buildings and the associated mechanical and electrical systems grow more advanced and environmental resources become more limited, building operators will need to improve building performance while reducing resource consumption. This will require a new dynamic building model capable of synthesizing information from various sources and automatically controlling building systems to enhance the overall building performance. Current Computer-Aided Facilities Management (CAFM) systems do not meet the requirements of this new paradigm. An appropriate system would not only contain static information but also would maintain up-to-the-second dynamic information about building components and systems. Previous research efforts have made advances toward realizing practically applicable dynamic building models (also termed self-updating, dynamic, self-aware, sentient and cogitative building models by others).

The authors have developed a Building Information Model (BIM)–based dynamic building model that shows promising results based on an initial implementation. The details of the authors' implementation and the conclusions of the study are provided in (Fuller & Connor, in prep; Fuller 2009). The authors developed a unique system that operates as an extension to existing commercial BIM software, Autodesk Revit Structures 2009. The authors expect that as BIM software becomes more commercially available, more researchers will utilize BIM technology as a platform for advancing the state-of-the-art without rebuilding software components that already exist. From the authors' experience, utilizing a commercially available BIM system as the basis for a dynamic building model has both benefits and drawbacks.

This paper presents several benefits and limitations of utilizing a commercial BIM system, Autodesk Revit Structures 2009, as the model representation for a dynamic BIM system. A model representation is a data structure or schema used to store building information. Though this paper does not present an exhaustive list of positive and negative aspects of this approach, it does provide useful insight gained from the authors' experiences.

2 PREVIOUS RESEARCH

Current building information modelling research builds upon several decades of previous research in "building product modelling." Research by (Eastman 1975a, 1975b; Law & Jouaneh 1986; Gielingh 1987; Björk 1989) has defined the conceptual framework for building product models and provided the foundation for dynamic building models. Current research in product modelling research addressing issues of interoperability, integration with manufacturing, support for disaster management and the management impacts of IT in construction, to name a few (Jardim-Goncalves & Grilo 2010, Grilo & Jardim-Goncalves 2010; Björk & Laakso 2010; Babič et al. 2010; Bernoulli et al. 2008; Froese 2010).

Previous research in dynamic building models has focused on developing a framework to manage dynamic building information but has not specifically focused on operating within the native BIM environment. Specifically, previous systems were designed for one or more of the following specific tasks (1) building monitoring (2) automating building controls (3) disaster response information. Several previous researchers developed have new model representations for their specific domain.

Cogitative or self-aware building systems are described in (Mahdavi 2009, 2001) and are implemented in (Içoglu & Mahdavi 2007, Mahdavi 2008) to monitor and control building lighting systems. The building model representation described in (Brunner & Mahdavi 2005) is a domain-specific representation called the Shared Object Model (SOM). The SOM is not intended to represent all possible building components and attributes rather it is intended to represent a domain-specific subset of a building's data. In order to be compatible with non-SOM data sources, the SOM must be mapped to all other model representations.

(Wießflecker et al. 2008 & Bernoulli et al. 2008) describe an independent system that extracts information from computer-aided facilities management (CAFM) systems and BIM systems for disaster management. Their system can provide information on the current location of building occupants (e.g. emergency responders) by integrating information from inertial sensors with building geometry. Static building information is extracted from an extended CAFM model and a BIM model and is then linked with dynamic information provided by building sensors and on-site staff. The system allows emergency responders to manually identify damaged building components and initiate an automated ad-hoc analysis to determine the structural safety of the building. Wießflecker et al. do not describe in detail the methods used to integrate CAFM and BIM data but the literature suggests that it was accomplished using a custom data model. Conversely, (Nour 2010) describes a system that links construction product data with a Building Information Model using an industry standard schema called the Industry Foundation Classes (IFC). In Nour's system, data retrieved from various project stakeholders is merged into a software independent Building Information model that may serve as a resource through the lifecycle of the building.

The previous research describes independent systems that may map data to or extracting data from other building information sources such as BIM. Commercially available building information modelling systems have properties that make them well suited to serve as a platform for creating dynamic building models. A dynamic building model that is integrated into a native BIM software environment may reduce the need to translate information from one representation to another and will extend the utility of BIM models.

3 DYNAMIC BUILDING MODEL IMPLEMENTATION

3.1 *Overview of implementation features*

What follows is a description of several key features of a dynamic building model and a discussion of the primary benefits or drawbacks to its implementation in commercial BIM software.

3.2 *Data integration*

The main function of a dynamic building model is to synthesize static and dynamic building information. All BIM's include static information that describes the semantics of building objects as well as building geometry. Extracting or translating information may create inconsistencies or data loss. We may eliminate the opportunity for such errors by simply using data in the native BIM data structure instead of translating it to another schema before use. Operating within the native platform provides a simplified data integration between dynamic and static building data and does not introduce interoperability problems by incorporating new data schemas.

3.3 *Code development*

Writing the actual machine code to implement a dynamic building model is a formidable task and the work required to implement the code may be increase or reduced by using a commercially available platform. Developing an extension to existing BIM software requires access to either the source code or to an Application Programming Interface (API). An API is a code library written by the original software developers to allow independent software developers to write programs that will execute within their original software.

The authors used the commercially available Autodesk Revit API (Autodesk 2008) as the basis for their dynamic building model as shown in Figure 1. In many cases, the API functions simplified code development while in other cases the API presented obstacles that required additional code development to surmount the problem. Many of the challenges encountered by the author are specific to the chosen API, however the authors expect that several challenges are of particular importance for future researchers to understand: (1) Programmatic access to building data (e.g. automated retrieval of updated and modified model components) (2) Level of control within the native environment provided by the API (e.g. capturing user events and control of users' view).

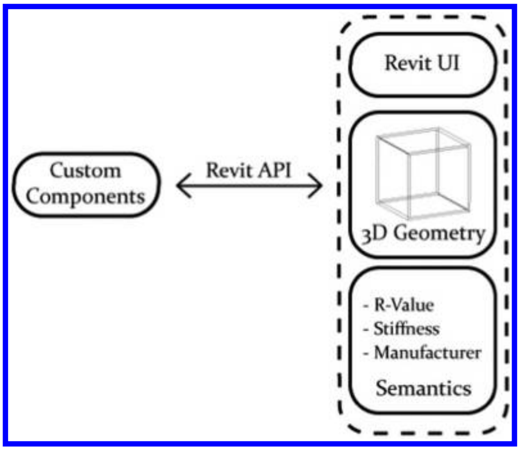

Figure 1. Custom components of the authors system were developed using the Revit API to access data in the Revit model.

3.4 *Graphical user interface*

The graphical user interface allows users to manipulate the building model in an intuitive graphical manner. As described in Section 3.3, the authors used the API for a commercially BIM software and took advantage of the existing user interface. Creating an extension of existing BIM system has the major advantage of being familiar to current users and does not require them to become familiar with a completely a new interface. Conversely, this approach also has the disadvantage of being inaccessible to users who are not familiar with the original system. A BIM-based approach may remain an attractive option because of the growing number of professional design firms investing in BIM technology (Gilligan & Kunz 2007). Standalone systems would require additional training which may discourage its use. Using the authors' proposed system, users may simply add a new toolbar to an existing BIM user interface and begin using it with minimal training.

A final key feature for dynamic building models is responsive graphic rendering. Dynamic information may be registered every fraction of a second and even a small facility may produce a large amount of instantaneous data that which may be challenging to present to a user. Graphical approaches (e.g. color coding hot or cold objects) should be preferred to purely text-based or tabular presentations because they allow users interpret data in an intuitive manner. For example, the authors implemented a feature that updated the graphical display of building model objects in "real-time" but found that the BIM system could not properly display the changing graphical information, perhaps due to a low view refreshing rate. This illustrates how seemingly small limitations may have a large effect on the final dynamic building model when working within a building model.

3.5 *Recommendations*

The authors recommend a BIM-based dynamic building model that closely integrates the static BIM data and the dynamic data but does not introduce interoperability problems. These features may also improve the utility of other dynamic building model systems. The use of a commercial API presented several obstacles that may be overcome by establishing research relationships with BIM software developers to gain access to source code or the development of open source BIM systems. Operating within an existing user interface offers benefits to current users at the exclusion of others. However, this obstacle may be overcome by extending the authors approach for operation within other popular commercial BIM systems or developing open source systems. Graphical rendering in the commercial BIM system did not properly display some fast changing building information. This limitation may be overcome by developing rendering interfaces that use commercial gaming rendering engines for dynamic building information.

4 CONCLUSIONS

Commercial BIM software is an attractive platform for creating dynamic building models. In this paper, the authors have presented several benefits and limitations of utilizing commercial Building Information Modelling (BIM) systems as the basis for dynamic building models. The authors implemented their approach and provided recommendations for overcoming the challenges. The authors future research will focus on (1) developing new approaches to integrating static BIM data with dynamic data (2) developing a framework for computational decision-making based on integrating BIM data and as well as other data sources.

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Use of standards for filling the gaps towards integrated BIM based ways of working—the InPro example

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ABSTRACT: This paper is focusing on the potential solutions provided by current Building and Construction standards to fill the gaps (missing or uncompleted functionalities) raised by new ways of working around a BIM based "Open Information Environment". The study focuses on different processes belonging to the Early Design Phase of a construction project. As a conclusion, solutions are proposed to fill some of the identified gaps.

1 INTRODUCTION

1.1 *Context*

This paper is inspired by the work done in the InPro project which main objective is to develop an "Open Information Environment" (OIE) supporting the Early Design Phase. In other words, we are aiming to establish and develop a model-based collaborative way of working that is relevant to the entire lifecycle of a building. Our vision in InPro is to achieve interoperability in buildings' early design phases through open standards. Among several issues raised by this "new way of working", we will concentrate for this paper on the current difficulties to implement BIM based scenarios and on the potential solutions provided by the use of standards. As a conclusion we will provide recommendations using BuildingSMART standards to provide answers to fill some of the identified gaps.

1.2 *The Key Processes*

InPro industry partners have selected in total seven different major Key Processes (KPs), which are based on their current knowledge and characterized the BIM implementation. In this paper six of them are mentioned. The analyzed KPs are presented briefly. More detailed presentation is available on the InPro web-site.

KP1—Coordination of architectural & building service design: It is raising a couple of general questions about integrated design based on a shared IFC model. The main identified gaps are related to Clash detection, quality control and change management as these points are essential concepts that are relevant for many design processes and thus should be solved in a way that is easily adjustable to serve other requirements.

KP2—Collaboration and approval workflow: KP2 is at the heart of any collaborative action and it cannot be considered outside the definition of a collaborative framework. Every study takes its hypothesis from other existing data, so every study must know the history and the validity of these data, among its lifecycle. If the link is kept with a project data global container, any user will take benefits from being informed.

KP3—Energy analysis: Energy analysis is for predicting the use and cost of energy in buildings. Energy analysis has a big role in the early design approach. This KP is impacted by many stakeholders, because the design solutions of the various disciplines in the design process have effect on the energy efficiency: building and spatial layout from the architect, properties of structures from the structural designer and system specifications from the HVAC and electrical designers. Additionally building owner and end users provide the main input for energy analysis.

KP4—Model based scheduling: Within the scope of construction scheduling, 4D visualisation is commonly the most desired application area of model based working and there exists already a range of commercially available software packages (Porkka & Kähkönen 2007). But several shortcomings of the available solutions still hinder the effective use of this new technique. Especially the isolated approach with a focus on visualisation only often doesn t give enough benefit to justify the very high effort necessary to set up and manage a 4D visualisation throughout several design iteration loops.

KP6—Client requirements management: This KP addresses the needs for a framework for communicating the objectives, needs, wishes and expectations of the client that describes the desired building. Processing of client requirements has a fundamental impact on the design, the construction and the whole lifecycle performance of a building. The client project goals are expressed in non-design terms and translated into targets and design requirements expressed and communicated in non-design terms and/or by using international standards.

KP7—Cost management: The focus of this KP is on investment cost and on life-cycle cost during early design phase. The aim is to enrich cost data during early design phase and to ensure re-usability of the data during later phases of the process. This means that both life-cycle and design estimates become gradually more accurate whenever a new piece of information is available.

1.3 *Methodology*

These scenarios, so called Key Processes (KPs), have been described from a traditional situation ("as is" situation) and then revisited to a BIM based way of working ("to be" situation). Then analyses of these BIM based KPs have been carried out. As a result of these analyses, several gaps have been identified in each KP. These gaps stress the missing functionalities or in a more generic way, the missing supports that could enable a smooth adoption of a collaborative environment focusing on the early design phase.

For each of these gaps or issues, we have formulated recommendations or actions that could at least tackle the identified issue or solve it. We have classified the identified gaps according to different classes of potential solutions. The table below shows the different classes of gaps and the related responsible or solution.

Among these classes, two are of particular interest in the scope of this paper, namely "Users Requirements" and "Standard".

The need for better user requirements is evident. The most difficult aspect here is more about how to produce such requirements, how to re-use and capitalise on existing requirements by just adapting them or including them in our needs. The identification and formal description of the KPs have appeared all along the InPro project as difficult and time consuming tasks. This exercise led us to elaborate Process Maps using the BPM Notation. This current result should be considered as a first step leading to a more formal description, of course encompassing the process map itself but also a description of the data exchanged among the sub-processes mentioned on the process map and as far as possible the technical solution binding the exchange requirement with an existing exchange format (IFC).

Table 1. Gap's categories.

Category	Responsible / Solution
Lack of data exchange use case (requirements & implementation guidelines) definitions	Users (requirements) / Standard / Software
Information definitions' scope of data exchange/sharing standard	Standard
Information sharing concepts of the data exchange/ sharing standard	Standard
Information scope of the software	Software
Domain functionality of software	Software
Data exchange/sharing content of software	Software
Data exchange/sharing functionality of software	Software
BIM content and structure	Users, modelling guidance

We at InPro consider openness and interoperability as the minimal mandatory conditions to have efficient exchange of information. The use of standards is the only solution to provide interoperability in our fragmented sector. This is particularly vital in a collaborative environment and even more in the Construction domain when collaboration is evolving rapidly depending on construction projects. Today, the different actors involved in early design are all using computer based solutions. But, as stressed in the conclusion of an InPro deliverable (InPro -D2 / 2007), most of the time there is an important loss of data when exchanging information (electronically) among these solutions. To that regards, the chapter on Standardisation provides a short state of the art of the standards already in use in the construction sector and then in a second part comes forward with propositions or recommendations on how to bridge some of these gaps by using relevant standards.

2 GAPS

The main gaps identified in the different KPs are summarized below.

2.1 *KP1—Coordination of architectural and building service design*

The main gaps identified are:

- Coordination of openings for HVAC equipment;
- Clash detection;
- Quality control of design solutions.

2.2 *KP2—Collaboration and approval workflow*

Several problems were raised concerning the exchange of data based on IFC. Some root attributes such as GUID and "OwnerHistory" are poorly managed. The GUID are not stable and the changes are not managed. This KP stresses also the need for a better integration of collaborative functions (definition of partner's roles & rights/partial views /etc.).

2.3 *KP3—Energy analysis*

The main output of the analysis performed for this KP is about the need for a better quality. The quality of the information stored in a BIM is currently hard to estimate as there are no common agreements on it. There is even a need to extend IFC properties to take into account these new data.

2.4 *KP4—Model based scheduling*

The analysis shows the lack of "model based" practice in 4D simulation and stresses the reasons that brake such adoption (import/export issues, insufficient visualisation capabilities, lack of open software, need for specific breakdown objects oriented towards scheduling needs instead of structural needs/etc.) (Tulke, 2008).

2.5 *KP6—Client requirements management*

It appears that at present the ICT support is "basic" and the manual processing of client requirements relies on individuals more than on collaborative work based on multi-disciplinary knowledge and joint goal and ICT support. It is essential that the ICT support facilitates a flow in data creation and decisions—minimizing rework. Decision making should be based on best possible (updated) data, after a decision; there should be no going back.

2.6 *KP7—Cost management*

This KP emphasizes especially the collaboration between construction and building services. The analysis shows the poor quality of information exchange among partners (Missing data and properties/use of different units/etc.).

3 PROPOSITION FROM STANDARDS

The different lists of gaps identified in the previous chapter prove that the InPro new way of working, based on a centralised BIM approach, is not applicable directly today. Actually, and it is not surprising, a first glimpse at the gaps shows that the main expectation revolves round the need for better integration and support of the information produced all along the selected KPs. Such expectation addresses directly the need for harmonised, shared ways and tools for working in a collaborative environment. The use of standards is the answer to provide interoperability and common understanding all along the exchanges. Among the difficulties linked to the exchange of information between multiple partners, the critical aspect is to ensure a semantic interoperability among partners. This semantic interoperability is obtained when actors of a considered process are able to share meaning or in other words when actors are able to understand each other. Achieving this semantic interoperability implies to have a technical interoperability (structure and format of the messages exchanged) but also common and agreed framework stating what to exchange and why (formalisation of the process).

The present chapter starts describing what the needs for an efficient semantic interoperability are. Then technical and organisational solutions that enable the semantic interoperability are described. The analysis of the KPs performed in the previous chapters has led to a gap list for each of them. These gap lists stress the missing functionalities that could enable a smooth development of each KP based on the OIE as a central point for collaboration and sharing. The final aim of this chapter will be then to identify these functionalities and the underlying data and propose solutions relying on the use of standards. Because of the context of the project, sector-based standards will be privileged in the proposed solutions.

3.1 *The need for interoperability*

The Interoperability need leads to the adoption of common, shared, agreed solutions. To play the role of a reference, available and usable for all, these references have to be maintained by neutral standardisation bodies. BuildingSMART defines the three mandatory pillars to support an efficient exchange of information as follow:

1. The format for information exchange must be shared and unique (how to exchange),
2. The information exchange has to be based on a common, standardized understanding (what is ex-changed), and
3. The orchestration of the exchanges has to be specified (when is it ex-changed).

The answers provided by BuildingSMART for these pillars are:

1. IFC as a common exchange language;
2. IFD as a formalised way for representing our vocabulary;
3. IDM as a formalised way to express and represent processes and data ex-changes;

These three items represents the prerequisite for a true computerized interoperability between two or more information parties.

3.2 *The need for collaboration*

Interoperability through a common semantic data model, like mentioned in the previous paragraph is enough for point to point exchanges specially for exchanging snapshots of the building project at a given lifecycle stage. When it comes to collaboration, needs for collaboration processes and data management arise. InPro has identified that simply exchanging data is not enough; instead data sharing is needed introducing notions like data access rights, data ownership, organizational and disciplines based data context, change management, versioning management and approvals. Those notions are needed in the identified InPro KPs in order to (for instance) compare different design proposals (from different stakeholders), trace information changes and data validity, filter data (not all the building information data is needed for each stakeholder—only the required data for the work to be performed), consolidate data from multiples sources, etc ...

For managing data along the collaboration processes the international standard PLCS (ISO 10303-239) is used for filling the gaps the IFC data model can't solve. Therefore the OIE is recommended to be based on that standard and fed by (but not only) IFC data streams. The usage of PLCS is not detailed in this paper and will be explained in a next paper.

3.3 *Recommendations regarding the gaps*

The aim of this chapter is to organise the different gaps identified and categorised as Users Requirements/ modelling issues or Standardisation issues. The first step consists in placing these gaps along one generic/ high level process and then explains how methods and standards could bridge them.

3.3.1 *Organisation of the gaps along a generic process*

Regarding the work issued by key process owners and other partners of the InPro consortium, Eurostep has established a generic key process so called "Coordination Process" which encompasses into a single and simplified view the different KPs. This Coordination Process could be represented as shown in Figure below.

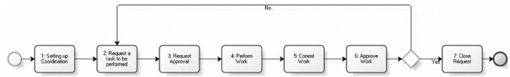

Figure 1. The Coordination Process.

The seven steps of this coordination process can be described as follow:

1. *Setting-up Coordination*: The main lead in this task is to organise and make explicit the exchanges among partners based on the use of the collaborative plat-form as a central node. Defining these exchanges consists in making an agreement on the work to be performed (client requirements) and on the way it will be performed (collaboration rules; technical environment).
2. *Request a task to be performed*: This is a basic collaborative task. An actor receives a request to perform a work. Details of the request should have been discussed earlier (during the setting-up of the collaboration). These details could be for instance the definition of the expected results, a deadline, etc…)
3. *Request approval*: Having received the request, the actor has to approve it, stating in that way he agrees to perform the work under the conditions expressed in the request.
4. *Perform Work*: According to the different KPs and the request received, the actor will perform a study, an analysis, a design work, a meeting or a review…
5. *Commit Work*: having performed the requested work, the actor has to commit it. This means, the work done has to be recorded into the collaborative system. The commitment can take several levels (proposal, draft, revision, final, etc.).
6. *Approve Work*: Approver(s) (defined in Setting-up Coordination task) receive a notification of the work committed. According to the work request, they control the work and make a decision (Approved/not Approved—If not approved, there is an iteration starting with a "Request a task to be performed").
7. *Close Request*: The committed work has been approved.

After a first analysis of the different gaps, the ones categorised as "User requirements" / Users Modelling Guidance or "Standardisation" have been placed along the process as described by the figure below.

Then we have tried to identify similarities among the gaps and to propose solutions relaying on standards. The results are presented in a table organized with the following columns:

– Gap Category;
– The Gap itself as previously identified;

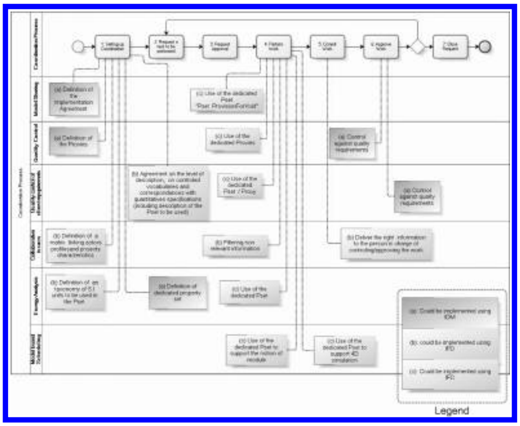

Figure 2. Location and identification of propositions along the Coordination Process.

- The KP(s) concerned;
- The missing/needed Functionality(ies);
- A proposition of Standard support;
- (if appropriate) Standards extension needs;
- Locations of the solution along the generic process.

The Figure 2 shows where the different proposed solutions take place along the coordination process.

It is interesting to notice that most of the gaps need a two steps answer. The first step consists in defining explicitly the exchanges what will be performed. The importance of the task 1 (Setting-up Coordination) is crucial to map the meaning of the data to the exchange structure. Having done this first step, the next consists in implementing the right structure (Pset or Proxy) to convey the meaning during task 4 (Perform Work).

3.3.2 *IFC Property sets and proxy*

Many of our recommendations provided above are promoting the use of Property Sets and Proxies. It is important to stress the assets of such mechanism. Most of the IFC objects can have properties attached to them. The IFC model differentiates between attributes that are directly attached to the object as attribute of the entity, and properties, group in a property set and assigned to the object by a relationship. The latter is the more flexible way to extent applicable properties.

Furthermore these properties may be specific to particular regions, projects or process. The IFC schema supports storing and transmitting these properties in named sets (so called property sets). Therefore, a property set is a collection of properties that can be declared outside of the IFC schema but that can assigned to all objects defined within the IFC schema (including proxies).

In the case of a BIM way of working and a process driven approach, we can imagine that property sets commonly agreed by parties could support the Information delivery. There-fore, the purpose and structure of such property sets could be declared as a standard.

Therefore, in the case of InPro, we can imagine Proxy objects well suited to support the needs of the various KPs. These "ad hoc" proxy objects could be an aggregation of relevant property sets according to the KP concerned. This could be a way to define explicitly the requirements for an efficient data exchange.

The management of collections of property sets and collections of proxies could be done trough the support of IFD mechanisms as illustrated by the figure below.

A proxy object could be defined with several facets according to the different contexts in which this object is used. On the OIE, the full description of the object will be stored but for exchange purposes (import and export) in an identified scenario, only needed proper-ties will be selected. This will provide several advantages (reducing the weight of the IFC files, quicker upload/download of data, easier quality checking…).

3.4 *Towards collaboration*

In front of all gaps "tagged" as "standards" or "User Requirements" (see description of categories in Table 1) we have made standard based propositions and shows that most of them could be solved by using existing appropriate mechanisms of the IFC. Some issues are out of the scope of this study (for instance, the management of the GUID tackled by the use of the PLCS standard).

The collaborative approach shows the need to change the current way of working and the current way of exchanging data among partners.

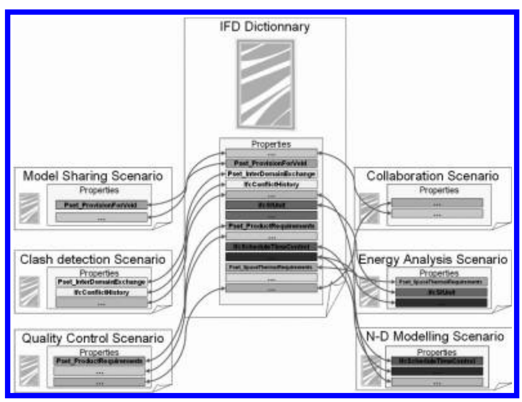

Figure 3. The IFD context mechanism to support different views of an IFC object.

IFC has to be considered as a robust and mature exchange format only. Our analysis shows that in most cases, it is not necessary to create a new basic object to bridge a gap. The basic blocks are there. It is just necessary to come with more "high level objects" that are well suited for identified processes. As a consequence, there is a need to define explicitly a priori exchange protocols adapted to the identified cases (e.g. our KPs).

This need could be satisfied from the technical point of view by using/defining adapted Proxies and Property and from a collaborative point of view also by using/applying methods facilitating the formal description of the whole process (IDM). IFD provides an open mechanism to support the multi-facet aspect of IFC objects (see illustration Figure 3 above). IFD makes also the semantic link between client requirements often expressed by qualitative indicators (common words) and technical specifications expressed by values and physical units.

It is necessary to well identify and differentiate functions/functionalities dedicated to collaborative work and those technical which should be supported by the IFC. On that particular point, we have reported that the implementation of the IfcOwnerHistory is not satisfactory. The new way of working imposed by a collaborative approach leads to develop new and enhanced ways for tracking changes by using the PLCS standard. This point has been particularly tackled in a deliverable available on the InPro project web-site (Overview of Information Management Applications, Including Object-Based Version Management—M.Nour et Al) and the usage of PLCS for adding the data management aspect to IFC will be demonstrate in the final InPro demonstrations.

4 CONCLUSION

The work performed in this task concentrated on the analysis of the key processes against the InPro's new way of working based on a collaborative approach relying on the use of a so-called OIE. Compared to the current way of working, this new integrated and collaborative approach needs improvements at different levels. We look as well to the changes in the process and information flow as to the changes of the information itself. This was the main outcome of the key processes analysis. The main output of this analysis is that IFC holds most of the necessary objects needed to fix the gap list items. What is necessary is to add more semantics to the relatively abstract terms available in IFC and describe the process around them; this could be done making use of IFD and IDM standards. When it comes to share data (collaboration), the PLCS standard is used for the management, the consolidation and coordination process aspects

5 ACRONYMS

BIM: Building Information Model/Building Information Modelling
IDM: Information delivery Manual
IFC: Industrial Foundation Classes
IFD: International Framework for Dictionaries
InPro: Open Information Environment for Knowledge-Based Collaborative Processes throughout the Lifecycle of a Building
GUID: Global Unique Identifier
KP: Key process [InPro]
OIE: Open Information Environment [InPro]
PLCS: Product Life Cycle Support.

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Collaboration and process modelling

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An open workflow-oriented distributed computing system

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ABSTRACT: Existing Distributed Computation Platforms (DCPs) facilitate the sharing of heterogeneous resources such as data, programs and computer clusters over local or wide-area networks. DCPs offer several benefits to the end-users such as improved effectiveness, efficiency, wider access and better use of existing resources. On the other hand, a vast number of standards related to distributed computing have spurred in the past decade, thus making it impossible to share distributed applications within and across engineering and scientific communities. In order to address this problem several components for open workflow development and management were developed. Based on these components it is possible to build and share distributed applications on an Internet-wide scale. Particularly, by using the developed components is possible to enable various engineering programs and data, contributed by organizations and individuals to be used in distributed applications. The validity of the approach is demonstrated by implementing few existing stand-alone engineering applications as workflows.

1 INTRODUCTION

Distributed computing has the potential to facilitate sophisticated resource sharing via local and wide area networks by improving performance, scalability, access and resource exploitation (Foster, Kesselman, Tuecke, 2001; Plaszczak and Wellner, 2006; Sotomayor and Childers, 2006; Antonioletti et al., 2005). Moreover, distributed computing techniques may contribute to the development of high-added value services in the civil engineering sector. This has been demonstrated by several applications developed in the past years for areas, such as structural analysis, process optimisation, provenance tracking for product models, and federated digital repositories (Trnkoczy, Stankovski, Turk, 2006). The complexity of these applications is high as they utilize heterogeneous distributed resources including data, programs, services, storage and computing clusters.

However, despite several waves of distributed computing-related research and development projects, distributed applications are currently still used to a limited extent, typically by elite stakeholders. Meanwhile, the majority of domain experts, who are in great needs of building and running distributed applications, are left out of the equation. This is partly due to the fact that grid computing itself is a novel field of research and relevant standards and technologies are still evolving.

One of the specific focuses of this study was distributed data mining. Distributed data mining applications may facilitate the automated extraction of potentially useful information from large and/or geographically distributed data volumes (Stankovski et al., 2008a). However, enabling data mining applications to be used in distributed computing environments is difficult to achieve due to a number of factors. There exist numerous data mining technologies and domain-oriented application scenarios (Kumar, Kantardzic and Madden, 2006; Guedes, Meira and Ferreira, 2006; Stankovski and Dubitzky, 2007; Conguista, Talia and Trunfio, 2007; Dubitzky, 2008).

In the past years, a number of use cases from the area of distributed data mining were collected and their requirements were analyzed. Along with the classical requirements related to scalability and speed-up, the following additional requirements were defined:

1. the domain experts should be able to build distributed applications by using a generic editor i.e. a front-end, which should hide the complexity of the underlying distributed computing infrastructures;
2. sharing, discovery, reuse and modification of existing distributed applications should be made possible;
3. distributed applications should include mechanisms for identity management, trust, and provenance tracking, if they are to be used securely, trusted and if they are to be interpreted unambiguously and reused accurately.

Particular focus of the present study is to investigate how existing, stand-alone engineering applications can be enabled and subsequently shared, discovered and executed on a distributed service infrastructure.

Scientific workflows offer an attractive and effective approach to the above requirements. By using workflows, it is possible to efficiently link distributed data resources and analytical tools together through domain-specific graphs representing work dependencies, computational tasks or information/data flows. In this context, workflows promote the next level of virtualization beyond services.

The result, which is presented in this study, is an open workflow-oriented distributed computing system, which can be used in several engineering areas for developing and running high-performance or high-throughput computing applications. An enabling back-bone of the developed system is a distributed metadata infrastructure, which conveys information about all the applications available in the environment. The system itself consists of existing and newly developed components. These are the Triana workflow editor and manager, Globus Toolkit 4, DataMiningGrid information services and the GridBus resource broker.

2 RESOURCES

There are numerous, heterogeneous resources which are used in distributed applications. It is important to realize that in order to be able to share resources in a distributed computing environment it is first necessary to describe them in a uniform way and publish these descriptions in the environment. The users can then search for these resources and combine them into complex distributed applications.

Resources, which may be shared when building and executing distributed applications include:

- **Data:** The data which may exist in the form of relational databases, data files (documents in various formats) and directories consisting of collections of documents;
- **Programs:** Engineering programs providing the implementation of various algorithms used to analyze data. A program, application or algorithm is an executable with associated input data, output data and parameter settings. The executable can be anything starting from a Java, C, Python or a BashShell program;
- **Computational machines and clusters:** Computational machines can be described by parameters, such as speed, occupancy, memory which can be used during processing, architecture etc.;
- **Storage:** Data storage devices to physically store the input and output data of engineering applications. For storage devices it is mainly important to have the ability to reserve space in advance, and to have safe and fast mechanisms for storing and retrieving data. Should storage be used for storing relational databases, than the necessary server-side software is also essential to be implemented on the actual site;
- **Streaming devices:** Sensors and other devices streaming data in a network are special kind of resources; and
- **Networks:** Optimisation of network parameters plays an important role in time-critical applications.

All resources from the list above have different parameters that should be considered when developing a distributed application. For example, certain resources can easily be moved in the network (e.g. data, programs and associated libraries) by using existing transfer protocols (e.g. ftp, GridFTP or RFT), while other resources are geographically distributed and can not be moved (e.g. computational machines, sensors, nano-ICT devices).

Another important observation is that in a number of scenarios for distributed data mining applications, it is impractical or impossible to move the data in the network. This may be due to variety of reasons, for example, large amount of data or security restrictions. In such cases, it must be made possible to move and execute the data mining programs at the location, where the physical data are stored.

3 OPEN WORKFLOW EDITING AND MANAGEMENT

In order to address the requirements, new workflow-editing software components were developed and integrated with an existing workflow editor and manager called Triana. Triana is an advanced system for editing and managing workflows, which is used as a user interface to Web services (Churches at al., 2005) and recently also as a user interface to grid services (Stankovski et al., 2008a). Workflows developed in Triana are complete and self-defined, and represent a far more effective mean of sharing knowledge, processing, communication, storage or content of computational tasks than the more elementary building blocks that are represented by individual services. The developed end-user components may be used from within Triana in order to link data resources, analytical tools and computing processes together in a form of various domain-specific graphs representing information flows and/or computing tasks. By using this workflow editor it is possible to develop distributed applications which are tailored to the specific needs of the various end-user types: information-technology specialists or domain-experts.

4 GRID MIDDLEWARE AND SERVICES

The GT4, Condor and the DataMiningGrid high-level services are ready-to-use WSRF-compliant services, which were used to build a test-bed for this study. Following is a brief account of the most important services and components.

4.1 *Globus toolkit 4 middleware and services*

A grid middleware toolkit implementing the WSRF v. 1.2 specification is the GT4 (Foster, Kesselman and Tuecke, 2001). GT4 provides a range of grid services that can be directly used to build a distributed grid environment. These include data management, job execution management, community authorization services etc. All these services can be used to build custom grid applications, and are elaborated in detail elsewhere (Sotomayor and Childers, 2006). GT4's ready-to-use services include WS-GRAM, GridFTP, RFT, MDS4 and were used to build the test bed for this study.

4.2 *Condor*

Scheduling of grid jobs in local computing clusters can be achieved by using the Condor middleware. Condor is specialized workload management software for submitting compute-intensive jobs to local computational clusters, which has been described in detail elsewhere (Thain, Tannenbaum and Livny, 2005). In our case, the GT4 submits a subset of parallel jobs to appropriate Condor clusters, and it is up to the Condor software to place them into a local queue, choose when and where in the local cluster to run the jobs, monitor the progress of the jobs, and ultimately inform GT4 services upon their completion.

4.3 *High-level services*

In addition to the core grid services provided by GT4, other high-level WSRF compliant, ready-to-use grid services have been developed under the DataMiningGrid project. Here, we provide a brief overview of the Resource Broker and the Information Integrator Service. These services fully support the parallel execution of a variety of (batch-style) programs in the distributed computing environment.

- The Resource Broker service is responsible for the execution of engineering and data mining programs anywhere in the grid environment. It provides a matching between the request for program execution, which is also called a job in grid terminology, and the available computational and data resources in the grid. It takes as input the computational requirements of the job (CPU power, memory, disk space etc.) and data requirements of the job (data size, data transfer speed, data location etc.) and selects the most appropriate execution machine for that particular job. The job is passed on to the WS-GRAM service and executed either on an underlying Condor cluster or by using the GT4's Fork mechanism. The Resource Broker service is capable of job delegation to resources spanning over multiple administrative domains. The execution machines are automatically selected so that the inherent complexity of the underlying infrastructure is hidden from the users. The Resource Broker service performs the orchestration of automatic data and application transfers between the grid nodes, using the GridFTP component of GT4 for the transfers. The Resource Broker is designed to execute multi-jobs. Multi-jobs are collections of single jobs that are bound for parallel execution. In DataMiningGrid, a multi-job usually consists of a single program, which is instantiated with different input parameters and/or different input data sets. The individual jobs are then executed in parallel on various computational servers in the grid environment. Each job, therefore, represents one execution of a program (i.e., an executable) with specific input parameters and data inputs. The Resource Broker makes extensive use of the associated Information Integrator service.
- The Information Integrator service provided by DataMiningGrid operates in connection to the MDS4 service provided by GT4. The Information Integrator service is designed to feed into other grid components and services, including services for discovery, replication, scheduling, troubleshooting, application adaptation, and so on. Its key role is to create and maintain a register of grid-enabled engineering and data mining programs. By doing so, it facilitates the discovery of grid-enabled programs on the grid, and their later use through the Resource Broker service.

5 AN APPLICATION DESCRIPTION SCHEMA

The main function of the open workflow-oriented distributed computing system is to facilitate the sharing of resources within a grid environment and to support the development and sharing of distributed applications. Our generic approach had to take into account the unique constraints and requirements of programs with respect to the data management, their execution requirements, the end-user interfaces, security needs and so on.

In order to cope with the complexity of resources in a dynamically changing grid environment, a novel metadata model was developed, which has a form of an XML schema. This schema is called an Application Description Schema (ADS) and defines properties necessary to describe engineering and data mining applications in a uniform way. For example, the XML schema provides properties to describe a data mining program and all its input data, output data, parameter settings and so on. Moreover, the ADS can be used to describe any program i.e., executable in general.

The ADS consists of two parts, which are:

- A common part, which can be used to describe any program, i.e., not necessarily data mining or engineering programs; and
- A domain-specific part containing additional information relating to programs, e.g., the program's application domain(s), the name of the atomic algorithm, the problem solving technique etc.

The common part of the ADS is subdivided into:

- General part that contains definitions of properties of the program, such as a unique ID, the program's name, vendor etc. This information is used to build a grid wide registry of available programs;
- Execution part contains definitions of properties related to the execution of the program. This includes the application type (Java, C, Bash Shell or Python), the location of the executable in the grid, list of libraries required for execution etc.;
- Application part provides definitions of properties needed to use the program. This includes options, data inputs and outputs, parameter lists and loops, requirements, environment variables etc.

The ADS adds a great range of functionality to the system. It is used through the whole execution process in the grid environment, beginning from the registration of programs through program discovery, selection, parameter, and input data specification to the actual execution of the program on the grid.

6 GRID-ENABLING PROGRAMS

A program (for example, containing sophisticated algorithm) is grid enabled when it is made available in the distributed computing environment so that the end-users can actually share it and make use of it, hence, the program may be considered a grid resource. To cope with interoperability and other high-level aspects it is necessary to provide an extensive description of each program by means of the ADS.

From an infrastructural viewpoint, all executables and their associated libraries represent files. Any program that can be invoked from command-line and is implemented to run without a graphical user interface, can be grid enabled (batch-style executables).

A predominant variety of general and domain specific programs can be adapted to be invoked from a command-line. For example, input data, output data, and parameter settings can be presented to a program via the command-line, using a specific format, e.g. a flag followed by the associated value ('flag <space> value', e.g., '-number 77'). Additionally the program may have system requirements like needed minimum free disk space, minimum memory or required operating system, which have to be specified in order to later execute the program on appropriate computational machine(s) in the grid.

Execution of algorithms in the grid is based always on a valid description of the prerequisites the implemented algorithm needs. The ADS can be used to describe the implemented algorithms including all their parameters, necessary input/output data formats, environment prerequisites and so on.

6.1 *A Web application*

By using the ADS schema, the developers can create a very detailed description of their program, which guarantees that it will run successfully and on the other hand provides information for its discovery on the grid. This description is always provided by the developer of the distributed application, someone who may not be acquainted with the underlying grid system.

The presented solution is a very simple procedure: the actual program i.e., executable is uploaded on a grid server and an ADS instance that describes the program is prepared and registered with the underlying Information Integrator service.

To speed-up the grid-enabling process, a Web application was developed, which consists of several form-based jsp web pages, leading the user through the whole process of creating and uploading his program on a server. The following Web pages are provided: General information, Execution information, Input data specification, Output data specification, Requirements specification, Executable and libraries upload.

6.2 *Life-cycle of the ADS instance*

The ADS instance file contains all invariant properties of the respective program (e.g., system architecture, location of the executable

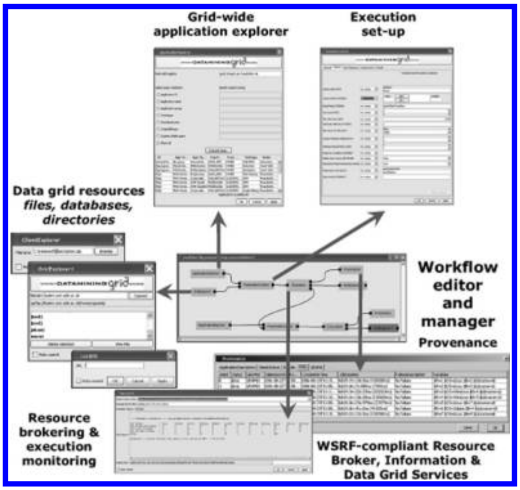

Figure 1. Workflow editing components.

and libraries, programming language). These attributes cannot be altered by users of the system, but are typically specified by the developer of the program during the process of publishing the program on the grid. The ADS instance also includes default values for all options, but the exact values are not set.

When querying for a program, the client side components (implemented as Triana units, see Figure 1) use the ADS instance in order to dynamically create a GUI, which conforms to the description of that particular program. For example, for each option a form field is generated, where the user can specify the values for that option. At this stage the user provides the exact values for the applications parameters (during runtime, e.g., application parameter values, data input, additional requirements) of the program.

7 TEST BED

A test bed was developed on the bases of the ready-to-use grid services discussed in the previous sections. It is a service infrastructure, with services running at various sites across different administrative domains in several countries.

The test bed provides a number of capabilities, the most important being the following:

- The ability to execute a variety of batch-style programs, at any appropriate computational server in the grid. These programs may be combined into complex-workflows, containing several multi-jobs executed sequentially;
- Meta-scheduling, i.e., dynamic and automatic allocation of optimal computational servers in the grid environment is achieved through the use of the Resource Broker, the Information Integrator service and MDS4.
- Program and data movement across different administrative domains is achieved through the use of the GridFTP and RFT services.

In addition to these, distributed computing environments based on GT4 and DataMiningGrid high-level services have a number of other capabilities, such as a Grid Security Infrastructure, which is described in Stankovski et al. (2008b). Over 20 existing programs have already been combined into distributed applications. To demonstrate the flexibility and extensibility of the developed software, we have developed applications for various sectors, such as civil engineering (e.g. by employing text-mining techniques), modelling of aquatic ecosystems (e.g. by employing machine learning approaches) and digital libraries. For example, an application in grid-enabled Federated Digital Libraries has been recently described by Trnkoczy, Turk, and Stankovski (2006) and Trnkoczy and Stankovski (2008).

8 CONCLUSIONS

Computational resources, data, algorithms, programs and applications represent valuable resources that could be shared on the Internet. The sharing of such resources has the potential to stimulate collaboration within and across scientific and business communities.

Resources, which are used in the investigated engineering scenarios include data, batch-style executables and associated libraries, computing clusters and storage facilities. Over 20 diverse applications have been built, also by domain experts by using the front end. The flexibility and extensibility of the workflow-oriented distributed computing system is mainly due to the use of the distributed metadata infrastructure, while the workflow editor appears to be a user-friendly tool for building distributed applications, which is accessible to non-programmers.

Many engineering programs require a repeated execution of the same process with different parameters that usually control the behaviour of the implemented algorithm or different input data sets. This is typically required in optimisation or sensitivity analysis tasks. Hence, resource sharing, performance, scalability, usability and security are critical for this kind of applications. The developed system is flexible enough to accommodate a variety of application scenarios, intra and inter community sharing, it is easy to use, conceptually simple, complies with emerging grid standards, and uses mainstream open technology.

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Development of a Cloud solution for SMEs in the Irish construction industry

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ABSTRACT: There is a strong emerging trend within the Information Communication Technology (ICT) sector for replacing traditional packaged desktop applications with Web based, outsourced products and services. The drive for this innovative solution is its contribution to enabling software to be developed, delivered and consumed in discrete chunks (known as services) liberating the users from traditional computing and providing services accessible across a range of devices and appliances. The objective of this paper is to report on the progress towards defining this Web based service, commonly known as 'Cloud computing', for Small to Medium Size Enterprises (SMEs) in the Irish construction industry. The authors will present the results of a Construction IT Alliance (CITA) Enterprise Innovation Network (EIN) marketplace survey that combined vendor and consumer attitudes. This paper will also act as recommendation for the future development of a re-engineered software solution that will utilise the benefits of Web services in the Irish construction industry.

1 INTRODUCTION

The use of ICT has proven instrumental in creating productivity gains within global markets, for example, through reduced transaction costs, scalability, and fast, reliable information flows and enhanced online collaboration tools and new ways to market goods and services (Pepper et al. 2009). The success and effectiveness of ICT in today's world economies have clearly shaped and improved the supply chain management process, communication ability and business, and still new innovative solutions are being adapted (Hore et al. 2009).

Hore et al, (2010) investigates the work of CITA in Ireland in encouraging SMEs interest in subscribing to a software marketplace that deploys an open source solution. The paper publishes the results of an EIN programme survey. The survey was based on a sample of 27 enterprises comprising of both customers and vendors. The overall results demonstrated the need for Cloud computing or something similar that would improve the competitive positions of SMEs in Ireland by allowing them to have access to software that was previously only the domain of large enterprises.

This paper is a continuation of the research involved with the EIN programme. It will present the survey results of almost 90 enterprises in the construction industry. Graphical analyses will be presented as part of illustrating the drivers, barriers, and benefits associated with Cloud computing and what this innovative concept means to the Irish construction SME sector.

2 THE SURVEY

The survey comprised of two samples customers and vendors in the construction industry. The structures of both questionnaires were designed to be similar, in order, to evaluate whether there is a strong relationship between the two samples. The methodology used for both questionnaires were designed on quantitative and qualitative research, which can be classified under two categories. Firstly exploratory research was used to diagnose a situation, screening alternatives and to discover new ideas. Secondly, attitudinal research used to subjectively evaluate the opinion, view or the perception of a person, towards a particular object. The principal difference between the vendor's and customer's surveys was the rephrasing of the questions in respect to one party engaging in providing applications and the other consuming one.

The survey was divided into four sections similar to a format previously tested by Hore and West (2005) with certain aspects of content referring to Naoum (2007). Each of the four segments was designed to analyse the potential of creating a business case study for Cloud applications in the Irish construction industry.

Use of ICT Up-take: identifying the overall business strategy of the respondents and their attitudes towards purchasing software and their use of ICT in the next three years. The purpose behind investigating this strategy was to establish the market requirement for SMEs.

Driving forces: the main attributes associated with attracting construction enterprises to use Cloud computing. The ten most standard types of drivers associated with using Cloud were presented in a ten point ranking scale format in the questionnaires.

Perceived Barriers to adoption: the industry's most common perceived barriers for rejecting the adoption of a centralized heterogeneous network based on OS principles. The ten listed barriers used in the questionnaires were based on secondary data collected from various national and international publications on this topic.

Benefits of Cloud computing: questions relating to opinions targeting the perceived benefits of Cloud computing. This question was presented as a likert scale to measure a range of options from "Strongly agree" to "Strongly disagree" in both questionnaires. The results of the perceived benefits could only assist in judging whether this service would be a success for SMEs in the Irish construction industry.

3 ICT UP-TAKE

The purpose of this section of the survey was to investigate a firm's management's strategy towards software and how the market views potential gains from future applications. The format of the questions in this section was based on the positivism approach of reasoning (the study of reality and beyond). This type of research relates to quantitative data analysis (factual questions). However, the majority of the questions were followed by an open-ended question which requires an interpretivism approach to qualitative data analysis (data expressed in words) (Peltomaki & Nummela's, 2004).

3.1 *ICT usage in construction in the next 3 years*

In identifying the markets philosophy on capital expenditure 32% of the combined vendor and consumer totals indicated a great increase in their firm's involvement in eBusiness and the use of ICT in the next three years. 50% of the respondents showed some increase while only 10% of almost 90 enterprises predicted no increase. Figure 1 illustrates the portions in graphical terms.

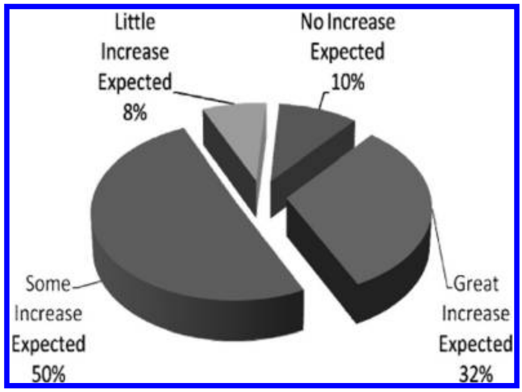

Figure 1. eBusiness and the use of ICT from the survey.

3.2 *SMEs low-uptake of ICT*

The sample singled out SMEs as the main attribute for the low level of ICT up-take in construction, coupled with the fact that the majority of construction firms in Europe are SMEs (97%, see e-Business W@tch, 2006). The respondents expressed an overall mixed reaction to this notion. Table 1 summarises the respondent's opinion to the statement, 'that the high concentration of SMEs in the construction industry is generally identified as the reason for the low ICT Uptake'. The most compelling result from this question is that the SMEs themselves view this as the reason (46%) in comparison to ICT vendors (26%).

One of the customers expressed that because they are constantly occupied they have a problem with identifying what applications are available and how these can benefit their business. They do not know where to start, with so much information online. A further question requested the respondents to express the reason for their answer. Figure 2 illustrates the tabulation of the responses in graphical form. 60% of the 40% of the respondents that disagreed with this statement were vendors.

In order to identify if vendors were developing products for the SMEs construction market the survey requested the vendors to state if they had identified construction SMEs, as a particular niche section for their software products. The initial response indicated a 71% positive assurance to the construction SME sector. However, after further analysis of the descriptive responses the figure increased to 87%. The interpretivism increase of 16% related to converting negative responses that actually indicated in their reasoning that any market using their product is a potential market. Other negative responses suggested that their services are marketed across a whole range of firms.

Table 1. SMEs the reason for low ICT up-take.

Opinion	Customer	Vendor	Overall
Strongly agree	13%	13%	13%
Agree	43%	26%	35%
No opinion	26%	39%	33%
Disagree	18%	19%	18%
Strongly disagree	0%	3%	1%

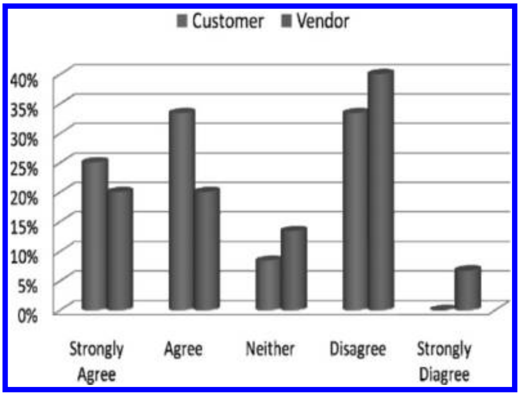

Figure 2. Qualitative analysis of SMEs as to the reason for low ICT up-take.

4 DRIVING FORCES FOR CLOUD COMPUTING

Both questionnaires requested each sample to rank in order 1–10 (10 being the highest) the factors that will attract or likely attract their organization to providing Cloud services. A summary of the overall results is shown in Table 2.

In combining both vendors and customers opinions Table 2 can act as an indication of how the construction industry perceives the valuable aspects of Cloud computing. The driver associated with a green solution surprisingly ranked the lowest in comparison to the highest driver value, 'added service'. The unprecedented decline in Irish construction may be a strong contributor as to why improving business needs is ranked high in contrast to sustainability needs. In separately analysing the two samples the ranking of the vendors and customers can be examined in further detail. Table 3 identifies the results of both samples.

The separate rankings of the samples in Table 3 summarises the correlation between the two results. The averages of all the values from the respondents of both samples were used to determine the overall ranking. Table 3 show that both payment flexibility and closer collaboration were ranked significantly differently by customers and vendors. The most concerning point to note is that customers have either not experienced the use of collaboration tools in the Irish construction industry or having availed of them, found their purpose to be surplus to their need.

Table 2. Drivers for Cloud computing.

Ranking	Drivers
10	Value added service—Improves the businesses product standard.
9	Sales—Increases market share.
8	Total cost—Total cost of ownership is predictable, visible, flexible and lower.
7	IT Costs—Eliminate IT costs and concerns associated with maintaining and upgrading separate applications.
6	Payment flexibility—Pay per user per month (user numbers can change per month).
5	Choice—select ICT solutions that are quick to deploy, easy to use, and will support your business processes.
4	Closer collaboration—more frequent communication and improve relationships along the supply chain and partner's networks.
3	Access—24 × 7 access from any online PC anywhere in the world.
2	Contract—No commitment (contract is month by month).
1	Greener solution—particularly for organisations that traditionally have operated their own data centres in regions with high electricity costs.

Table 3. Individual sample driver rankings.

Ranking	Customer	Vendor
Greener solution	1	1
Payment flexibility	4	8
Closer collaboration	3	7
Sales	10	9
Value added service	9	10
Contract	2	3
Total cost	8	5
Access	3	2
IT Costs	7	4
Choice	6	6

Figure 3 illustrates the data collected in Table 3.

The correlation scatter diagram is used to assess whether there appears to be a correlation between two measurements (Naoum, 2007). It is evident from Table 3 and Figure 3 that there is some divergence of opinion between the customers and vendors ranking opinions in relation to the question. The linear regression line in Figure 3 illustrates the trendline relationship between the

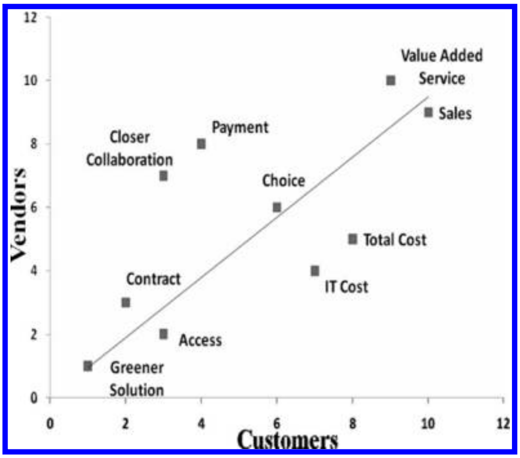

Figure 3. Correlation drivers of Cloud computing.

sample results. As indicated from the diagram, greener solutions and choice are two points on the line with sales and value added service being closely correlated with both samples. To conclude the correlation graph identifies that a few of the driving forces were ranked sufficiently close to the trendline to identify that there was a broad agreement between ranking.

5 BARRIERS TO CLOUD COMPUTING

The barriers for adoption question was formatted identically to the drivers question with both samples being requested to rank in order 1–10 (10 being the highest). The attitudinal barrier statements provided were collected from various perceptions of Cloud computing in the media and literature reports. Figure 4 illustrates the correlation between the two samples.

From review of Table 4, 'lack of awareness or knowledge' is ranked the overall highest. From this a comparison can be made with section 3.2 of this paper, the analysis relating to ICT up-take by SMEs. One respondent felt that there was too much information online in an unstructured format. This barrier is clearly evident in Table 4 overall rankings. The next major barrier was 'security'. Armburst et al. listed this as number 3 in their top ten obstacles and opportunities for Cloud computing (Armburst et al. 2009). The lowest ranked barrier was surprisingly 'contract'. In relation to the customers they ranked this the lowest and 'pricing models' ranked as third lowest.

The correlation diagram Figure 4 illustrates that there is some evidence of divergence of opinion between customers and vendors. benefits of Cloud computing.

The eight perceived benefits of Cloud computing were asked in both questionnaires. The actual statements relate to Ramanujam's (2007) key points as to why Cloud/On-Demand would be a smart choice for companies. Table 5 demonstrates the opinions of both samples (customers and vendors) in relation to Ramanujam's perceived benefits:

The results of the frequency distribution in Table 5 are graphically illustrated in Figure 5.

The combined responses to this question indicate that the majority of the respondents in the construction industry are in favour of the Cloud benefits. The percentages allocated towards disagree and strongly disagree are under 10%. The graph illustrates this by contributing the two

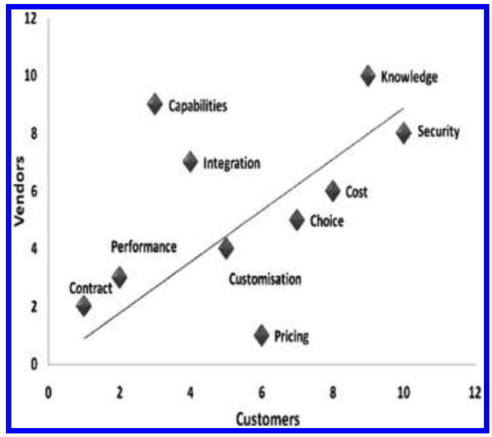

Figure 4. Correlation barriers on adoption of Cloud computing.

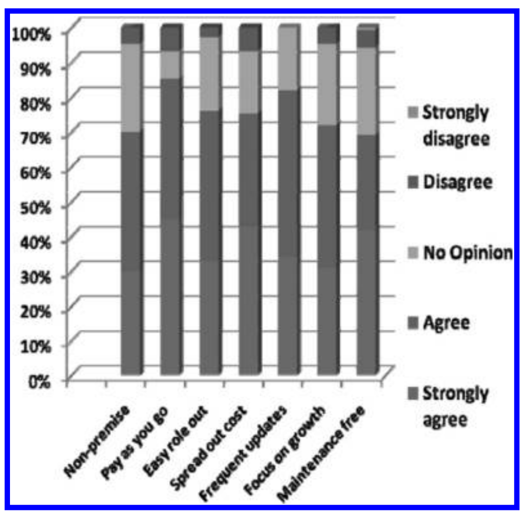

Figure 5. Perceived benefits of Cloud computing.

largest proportions of colours to strongly agreeing and agreeing (blue and green). Hore et al. analysed the results of this same question in their EIN survey which targeted customer members. The results of that survey showed that 67% of the customers were undecided as to the concept of having a service managed online. In relation to such benefits, as reducing capital cost of purchasing software and not having to worry about disaster recovery, 25% of the respondents indicated causation in relation to these benefit (Hore et al. 2010). Table 6 indicates the scores associated with this surveys customer respondents.

It is evident from Table 6 that overall the customers in the Irish construction industry are not concerned about having their services managed online.

Table 4. Barriers for adoption of Cloud computing.

Barriers	Customers	Vendors	Overall ranking
Knowledge—Lack of awareness or knowledge:	9	10	10
Security—Security concerns:	10	8	9
Cost—Total cost of ownership concerns:	8	6	8
Capabilities—Customers may not possess adequate eBusiness capabilities:	3	9	7
Choice—"We can't find the specific application we need":	7	5	6
Integration—Lack of integration and interoperability of software:	4	7	5
Customisation—Lack of customisation:	5	4	4
Pricing—Complicated pricing models:	6	1	3
Performance—Application performance:	2	3	2
Contract—"We're locked in with our current vendor":	1	2	1

Table 5. Perceived benefits of Cloud computing.

Perceived benefits of Cloud	Strongly agree	Agree	No opinion	Disagree	Strongly disagree
Non-premise	30%	40%	25%	5%	0%
Pay as you go	45%	40%	8%	7%	0%
Easy role out	33%	43%	21%	3%	0%
Spread out cost	43%	32%	18%	7%	0%
Frequent updates	34%	48%	18%	0%	0%
Focus on growth	31%	41%	23%	5%	0%
Maintenance free	42%	27%	25%	5%	1%

Table 6. Customers perceived benefits of Cloud computing.

Perceived benefits of Cloud	Strongly agree	Agree	No opinion	Disagree	Strongly disagree
Non-premise	52%	38%	7%	3%	0%
Pay as you go	64%	25%	7%	4%	0%
Easy role out	45%	38%	14%	3%	0%
Spread out cost	48%	31%	17%	3%	0%
Frequent updates	52%	31%	17%	0%	0%
Focus on growth	48%	34%	14%	3%	0%
Maintenance free	52%	24%	24%	0%	0%

Having the benefit of no facilities (non-premise) would enable one to focus their attention towards the customer instead of worrying about unnecessary ICT problems. In contradiction to the EIN survey, Table 6 shows that the customers are in agreement with both the benefits of spreading out costs (capital cost of purchasing software) and maintenance free (disaster recovery). However, in relation to the results of the combined scores (Table 5) both non-premise and maintenance free values did yield the highest percentage of no opinions. This 25% should be identified as the percentage of the industry that needs to be educated more on these specific benefits of Cloud computing. To conclude, the construction industry perceives the benefits of Cloud computing to be a positive addition in assisting them to becoming more effective and efficient.

6 CONCLUSION

The purpose of this paper was to illustrate the findings of a CITA EIN 2010 survey that highlighted the drivers, barriers, and benefits associated with Cloud computing in the Irish construction industry. The early results of this survey have strongly indicated a need for such a Web-based model that has the ability to promote collaboration between all construction disciplines. The results indicated that 'sales' and 'value added service' were the main incentives for adoption. In analysing the barriers the majority of the respondents agree that 'lack of awareness or knowledge' may deter them from implementing this service. However, the perceived benefits of having convenient on demand network access to a shared infrastructure, with elasticity and consumption-based pricing, has demonstrated to the Irish construction industry the capabilities of this new layer of internet architecture.

In conclusion the next stages of the development will require a small contingent of the Irish SME market to test a recommended developed service. It is envisioned that through the process of a development plan and in collaboration with EIN's SMEs an identified re-engineered software solution will be established. The applications provided for this solution will be chosen from the CITA's software directory. The need for such an innovative solution is to provide SMEs in the Irish construction industry with applications that can assist their construction methods becoming more efficient and effective in a global economy.

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Towards ontology-based business process management in construction

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ABSTRACT: Process control and management is one of the important aspects of a construction project. Use of ontologies for construction processes can serve for efficient information sharing and harmonisation, providing interoperability in systems with multiple heterogeneous resources and semantically inter-linking construction and process elements. However, ontological representation of such processes is still at the upcoming stage because of the high complexity of these processes, their highly dynamic behaviour and the short lead time of the construction projects. In this paper, we suggest a new methodology for ontology-based process management and provide details of the developed concepts and current results.

1 INTRODUCTION

To date, construction processes are modelled in a semi-formal business process modelling language like EPC (Event-driven Process Chains) or BPMN, the Business Process Modelling Notation (OMG 2008). In the execution phase, however, it requires a significant amount of manual work to adapt and maintain the business process. Therefore construction projects are typically managed only on the level of scheduling.

The formalisation of processes with the help of ontologies provides a way to support business process management on each stage of the construction project. An additional advantage of ontology use as a form of formalisation is the possibility to analyse business process inherent domain knowledge (reasoning, consistency checking, purpose-based search) and to reuse it.

The ontological process management includes such steps as registration and saving of process patterns, search of reusable process patterns, configuration and adaptation of reference processes for a specific construction use case, composition of more complex processes from the saved process patterns, instantiation of these processes and querying the process knowledge base. This goes beyond the usual process formalisation and semi-automatic process configuration. A key issue is thereby the development of executable *Business Process Objects* (BPOs). They can represent knowledge enhanced reusable process patterns, which can further serve for automatic process configuration, instantiation and analyses on logical basis. In this way comprehensive process-centred operability can be achieved, enabling more efficient and better controlled collaborative process management.

Formalisation of the current semi-formal process models will enrich these models semantically, enabling intelligent decisions and hence more efficient management solutions. However, an ontology for processes can also serve interoperability purposes, enabling the connection to other data models. The flexibility of structuring the ontology knowledge base allows the modeller to provide this integrating connection to widely distributed construction data models and heterogeneous resources, using different data formats and contained in the widely distributed repositories of the partners in a construction project.

2 RELATED WORK

For the development of an ontological approach to construction process management, related research efforts were investigated at the outset, including existing generic approaches for process representation.

BPMO (Business Process Modelling Ontology), developed within the European project SUPER, provides an innovative approach for the semantic representation of business processes, where meta ontologies for the formalisation of such process modelling languages as BPMN and EPC were produced (SUPER 2009). The following functions are provided in the application: process modelling and semantic annotation, search and retrieval, definition of process patterns, integration of the organisation's information, auto-completion of the processes, policy definition, graphical representation and validation. The methodology, by which the knowledge associated with business processes is collected, organised, distributed and used, is based on the Semantic Web Services technology (SWS). The implemented ontology modelling language WSML is Frame-logic-based. It uses WSMO (the Web Service Modelling Ontology) for the description of SWS (Roman et al. 2005). The close correlation between SWS and process formalisation widen the exploration environment. However, the objective of the work is not to find the technical means to implement the processes and to provide them as Web-services, but to examine the conceptual representation of the processes, to model it and to demonstrate the usage for the entire business process management.

In the context of scientific interest is also the Enterprise ontology suggested in (Dietz 2006). It describes the implementation-independent aspects of an enterprise, thereby achieving a common understanding of the entire enterprise. The developed model clarifies in coherent and comprehensive manner the ontological model of an organisation. This model consists of four views: Construction Model, Process Model, State Model and Action Model. The Process Model itself is focused on the presentation of the process structure, transaction patterns and sequences.

Another enterprise ontology was developed by Uschold et al. (1998). It contains various terms and definitions from the enterprise domain. Processes are described by activities, resources, plans and capabilities.

The Business Management Ontology (BMO) suggested by Jenz (2003) represents an integrated information model, which helps to better adapt IT with business objectives and brings together business process design, project management, requirements management and performance management. For this purpose, process-relevant basic concepts such as BusinessProcess, ProcessPattern, ProcessProfiles, BusinessObject are defined.

In the project m3pe (Multi Process Engineering Meta Model) a dedicated process ontology has been developed for the realization of workflow interoperability through a common unifying process model (Haller et al. 2006). The focus lies on the modelling of technical workflow aspects and specific process representations.

In the construction domain, a process model developed as part of the standardised IFC2x4 Project Model is available (IAI 2010). The IFC Process Extension includes the concepts *ifcProcess*, *ifcTask* etc. and attributes that show the essence of construction process flows. However, the conceptualisation level with regard to the overall business process management strategy is relatively low.

There are also many upper-ontologies that contain the term "process" (or "business process").

SUMO (Suggested Upper Merged Ontology) (Pease & Niles 2001) is derived from more than one available ontological contents and contains more than 600 concepts, including the concept of "Process" with the sub-concept "Intentional-Process" with the sub-concept "ITProcess" which is of particular relevance for business process management. The possible integration of Business Processes in SUMO has been described in (Thomas & Fellmann 2009). However, upper ontologies contain much information of lower relevance for a specific domain application. In practice, such ontologies are only rarely used because they require considerable domain level adjustments.

DOLCE (Descriptive Ontology for Linguistic and Cognitive Engineering) comprises a minimal taxonomy of about 100 concepts for representation of general common sense categories and is therefore called *ontology of particulars* (Gangemi et al. 2002). The concept of 'process' is hierarchically represented under Perdurant / Stative / Process. There exists already an approach for the integration of BPMN processes in the DOLCE ontology (Ghidini et al. 2009).

Business process management includes specific topics such as the analysis and development of a business architecture, business process modelling, business process composition and configuration, information retrieval and reasoning, business process optimisation and engineering, process integration, process discovery, business process quality measurement, business process monitoring, business process visualisation, transformation of business process models, business process evaluation, conformance and risk management, process planning etc. One of the applications of business process ontologies is the semantic annotation of the business processes. The goal of semantic annotation is the improved interoperability and information retrieval (Uren et al. 2006). Another important aspect is the formal representation of processes, which means the presentation with syntax and semantics of certain logic formalism. BPMN is formalised using WSML, i.e. F-logic based, in (SUPER 2009), and using OWL, i.e. description logic based, in (Ghigini et al. 2008). Semantic representation of EPCs has been proposed in (Kindler et al. 2006; Rybenko & Katranuschkov 2009; SUPER 2009). A process language independent (both BPMN and EPC) formalisation by means of OWL is shown in (Thomas & Fellmann 2009).

3 METHODOLOGY

The proposed methodology for ontology-based business process management outlined in this chapter is built upon the concepts of Business Process Objects (BPOs), initially suggested in (Katranuschkov et al. 2006). The formalisation of processes in a BPO

Ontology was first attempted in the European project InteliGrid (Dolenc et al. 2007) and further developed in the German project BauVOGrid (Rybenko & Katranuschkov 2009). In short, BPOs provide standard reusable process patterns, which can further serve for dynamic, IT-supported process configuration, instantiation and analyses on logical basis (Katranuschkov et al. 2009). The principal procedure is illustrated in the Figure 1 below.

Basically, the overall methodology of using a *Process Ontology* and related services comprises the following steps from the viewpoint of the user:

1. Finding suitable process patterns for the targeted overall process from the library of reusable process patterns saved in a process knowledge base
2. Adapting the selected process patterns to the specific context of use and saving them as BPOs in the Process Ontology
3. Configuring the BPOs for the specific use case
4. Inter-linking the BPOs with the data from other construction models required for their proper execution like BIM data, site data, organisational data, work specifications etc.
5. Composing the overall process by assembling the BPOs in a complete process network with the help of compositional knowledge rules
6. Instantiating the process and monitoring or controlling its execution.
7. Querying the process knowledge base during execution for further management decisions and operations, especially with regard to the connection of the process with other specific construction data or services.

All these steps must be supported by respective services. Such services are presently under development in the frames of the German lead project Mefisto (Scherer et al. 2010a).

4 TECHNOLOGICAL APPROACH

Construction processes can be further classified into *material processes* and *information processes*. Material processes take place on the construction

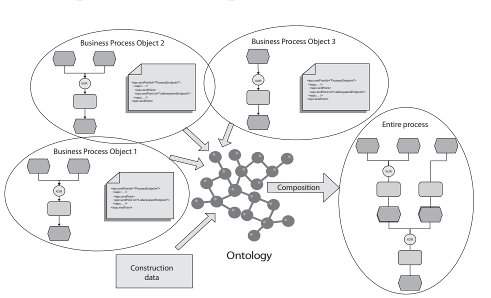

Figure 1. Process management by means of ontologies.

site and are also input for the information processes. In contrast, information processes take place in the information system and are associated with planning and decision-making procedures and the deduction of the relevant project parameters for these procedures (costs, schedules, risks etc.). In our approach, both types of processes are modelled using BPMN and formalised in OWL (W3C 2004), the Web Ontology Language based on *Description Logics* (DLs). DLs are a family of logic-based knowledge representation formalisms designed to represent and reason about conceptual knowledge (Baader et al. 2003). What makes description logics the formalism of choice is the fact that it defines a decidable fragment of first-order logic, i.e. queries for entailment of subclass relationships or class membership of a particular individual are effectively computable.

Elementary descriptions in DL are *atomic concepts* and *atomic roles*. Complex descriptions can be built from them inductively with *concept* and *role constructors.* A common DL level of expressiveness as basically available in OWL is ALCQI. ALC stands for a DL that allows only negation, conjunction, disjunction, and universal and existential restrictions, *Q* stands for number restrictions, and *I* for inverse roles. The main constructs available in *ALCQI* are listed in Table 1 below.

The semantics of *ALCQI* concepts is defined in terms of an *interpretation.* An interpretation *I* consists of a non-empty set Δ^I (the domain of the interpretation) and an interpretation function, which assigns to every atomic concept *A* a set $A^I \subseteq \Delta^I$ and to every atomic role *R* a binary relation $R \subseteq \Delta^I \times \Delta^I$. The inductive extension of the interpretation function to concept descriptions is also shown in Table 1.

Table 1. Syntax and semantics of ALCQI description logic.

Name	Syntax	Semantics
Top concept	T	Δ^I
Existentional restriction	$\exists r \cdot C$	$\{x \in \Delta^I \mid \exists y.\ (x, y) \in r^I \wedge y \in C^I\}$
Universal restriction	$\forall r \cdot C$	$\{x \in \Delta^I \mid \forall y.\ (x, y) \in r^I \rightarrow y \in C^I\}$
Negation	$\neg C$	$\Delta^I \backslash C^I$
Conjunction	$C \cap D$	$C^I \cup D^I$
Disjunction	$C \cup D$	$C^I \cap D^I$
At-least restriction	$(\geq n\ r\ C)$	$\{x \in \Delta^I \mid \#\{y \in C^I \mid (x, y) \in r^I\} \geq n\}$
At-most restriction	$(\leq n\ r\ C)$	$\{x \in \Delta^I \mid \#\{y \in C^I \mid (x, y) \in r^I\} \leq n\}$
Inverse role	r^-	$(r^I)^{-1}$

A DL knowledge base usually consists of a set of terminological axioms (called TBox) and a set of assertional axioms or assertions (called ABox). An interpretation *I* is a model of a DL knowledge base if it is a model for the ABox and the TBox.

An equality whose left-hand side is an atomic concept is called *concept definition*. Axioms of the form $C \subseteq D$ for a complex description *C* are often called *General Concept Inclusion* axioms (*GCI*). An interpretation *I satisfies* $C \subseteq D$ if $C^I \subseteq D^I$. Every concept definition $A \equiv C$ can be expressed using two GCIs: $A \subseteq C$ and $C \subseteq A$. Therefore a TBox can be seen as a finite set of GCIs. *I* is a *model* of a TBox *T* if it satisfies all GCIs in *T*.

An ABox assertion is of the form $C(a)$, $r(a, b)$, where a, b are individual names, *C* is a concept, and *r* a role name. An interpretation *I* additionally assigns to every individual name *a* an element $a^I \subseteq \Delta^I$. An interpretation *I satisfies* $C(a)$ if $a^I \in C^I$ and *I satisfies* $r(a, b)$ if $(a^I, b^I) \in R^I$. *I* is a *model* of an ABox *A* if it satisfies all assertions in *A*.

5 CURRENT DEVELOPMENT AND RESULTS

Using ALCQI description logic the proposed Process Ontology for the support of construction process management was developed. Currently, it is being extended and inter-linked with domain data models for the representation of various process-related resources, whereby a number of reference process patterns like the site process "Produce column" shown in BPMN notation in Figure 2 are being defined. The formalisation is done under consideration of construction project requirements and existing ontological representations of processes, whereby certain concepts of the studied ontologies were analysed and after harmonisation and adaptation included in the Process Ontology. The interfaces to other construction data models are presented as corresponding concepts in the ontology, namely: Costs, Specifications, Time Schedules, Construction Site, Building, Organisation, Risks.

Figure 3 shows part of the hierarchy of concepts in the Process Ontology. There are 4 main upper level concepts: *ConstructionTask*, *BPO*, *BPMN-Representation* and *Object*. *ConstructionTask* represents standard simple tasks like "form column". *BPO* represents more complex tasks as patterns, like "produce column", and is comprised itself of several simple tasks. *BPMNRepresentation* allows to capture related to the construction process BPMN diagrams, thereby enabling the sequential assignments between the process elements. Finally the concept *Object* reflects the connection of the Process Ontology with other construction data models, like IFC.

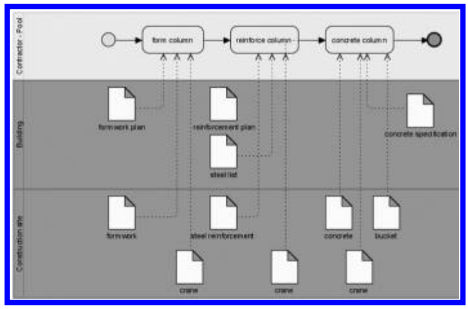

Figure 2. BPMN notation of the example reference process "Produce Column".

ConstructionTask ⊆ T
BPO ⊆ T
BPMNRepresentation ⊆ T
Object ⊆ T
SupportingConcepts ⊆ T
State ⊆ SupportingConcepts
Form_column ⊆ ConstructionTask
Reinforce_column ⊆ ConstructionTask
Concrete_column ⊆ ConstructionTask
Produce_elements ⊆ BPO
Produce_column ⊆ Produce_elements
Costs ⊆ Object
TimeSchedules ⊆ Object
Resource ⊆ Object
ConstructionSite ⊆ Resource
Building_IFC ⊆ Resource
Organisation ⊆ Resource
ConstructionDevice ⊆ ConstructionSite
IFCProductRepresentation ⊆ Building_IFC
IFCMaterial ⊆ IFCProductRepresentation
IFCProduct ⊆ IFCProductRepresentation
Element ⊆ IFCProduct
IFCColumn ⊆ Element
BPMNProcess ⊆ BPMNRepresentation
GraphicalObject ⊆ BPMNRepresentation
Artifact ⊆ GraphicalObject
ConnectingObject ⊆ GraphicalObject
FlowObject ⊆ GraphicalObject
Swimlane ⊆ GraphicalObject
Pool ⊆ Swimlane
Lane ⊆ Swimlane
Activity ⊆ FlowObject
Event ⊆ FlowObject
StartEvent ⊆ Event
EndEvent ⊆ Event
Gateway ⊆ FlowObject
Task ⊆ Activity
Association ⊆ ConnectingObject
SequenceFlow ⊆ ConnectingObject
Artifact ⊆ DataObject

Figure 3. Partial concept hierarchy of the Process Ontology.

The structure of these sub-concepts is similar to the resource concepts of interest, like *IfcProduct* and *IfcMaterial* in the IFC. Hence, the Process Ontology provides the backbone of a multi-model framework as developed in the Mefisto project and shown on Figure 4 below (Scherer et al. 2010b). However in the Process Ontology only the references to IFC and other models are defined. Therefore, to obtain the information about a concrete building object, a query for the concrete model data has to be executed.

Figures 5, 6 and 7 show the concept assertions, an example of two of the defined GCIs serving as constraints and the role assertions, respectively.

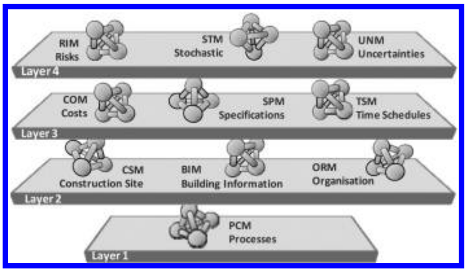

Figure 4. The layered modelling framework of the Mefisto project showing the integrating role of the Process Ontology.

```
Produce_element(inst_produce_column)
Form_column(inst_form_column)
Task(inst_form_column)
Reinforce_column(reinforce_column)
Task(inst_reinforce_column)
Concrete_column(inst_produce_column)
Task(inst_produce_column)
BPMNProcess(inst_diagram)
SequenceFlow(inst_seq1)
..
SequenceFlow(inst_seq4)
Association(inst_ass1)
...
Association(inst_ass11)
DataObject(inst_crane)
...
DataObject(inst_bucket)
Pool(inst_contractor-pool)
Pool(inst_building)
Pool(inst_construction-site)
StartEvent(inst_stev1)
EndEvent(inst_endev1)
ConstructionDevice(inst_crane)
...
ConstructionDevice(inst_reinforcement)
IFCMaterial(inst_beton)
IFCColumn(inst_column)
State(inst_produced)
...
State(inst_available)
```

Figure 5. Concept assertions in the Process Ontology.

$\exists isOutputOf.Produce\_elements \sqsubseteq Element$
$\exists isOutputOf.Produce\_column \sqsubseteq IFCColumn$

Figure 6. General concept inclusions of the Process Ontology.

```
hasSubTask(inst_produce_column,inst_form_column)
hasSubTask(inst_produce_column,inst_reinforce_column)
hasSubTask(inst_produce_column,inst_concrete_column)
hasInput(inst_form_column,inst_formwork)
hasInput(inst_form_column,inst_crane)
...
hasInput(inst_concrete_column,inst_bucket)
hasOutput(inst_produce_column,inst_column)
hasState(inst_crane,inst_free)
hasState(inst_formwork,inst_available)
...
hasPool(inst_diagramm,inst_contractor-pool)
hasPool(inst_form_column,inst_contractor-pool)
...
hasSource(inst_seq3,inst_reinforce_column)
hasTarget(inst_seq3,inst_concrete_column)
hasSource(inst_ass10,inst_bucket)
...
```

Figure 7. Role assertions in the Process Ontology.

Instantiation of all these assertions proceeds at run-time.

Specifically, the constraints shown on Figure 6 can be interpreted as follows: "The output of the task *produce elements* should be *element,* and of the task *produce column—column*". Whilst such propositions look obvious to a human, their formalisation enables unambiguous "understanding" of resource and process inter-relationships by the software—a prerequisite for efficient computer-supported process management.

6 CONCLUSION

Definition and use of a Process Ontology for construction process management reflects the needs for an IT infrastructure for efficient semantic collaboration in construction projects. It satisfies various management requirements and is well suited to support inherent process dynamicity in the construction domain.

Early results achieved in the projects InteliGrid and BauVOGrid have provided promising perspectives for further development of the methodology outlined in the paper. In particular, in BauVOGrid which focuses on defect management a similar methodology was effectively applied. The developed system of ontologies was successfully deployed and showed very positive results with regard to the complex defect management process both in the late construction phases and during the operation of a facility (test site: the new football stadium in Dresden, Germany). However, the formalisation of reusable reference process patterns is still at an early stage, and the Process Ontology itself needs further enhancement. The real practice studies that will be undertaken in the frames of the Mefisto project will help to refine and improve the developed ontology and the methodology of its use. This should also provide evidence of its wider applicability.

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Transformation of Business Process Models into Petri Nets for building process simulation

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ABSTRACT: The objectives of this research work are (1) to develop a new approach for the behavior analysis and simulation of the eEPC Models and BPMN Models, (2) to describe the transformation of eEPC and BPMN into PNs for the purpose of verification of Building Process Models. In this paper the transformation into Low PN is shown whereas the second objective is outlined on a conceptual level. For illustration, a construction process, modeled by eEPC and BPMN, is transformed into PNs. Behavioral properties of the model are checked, the simulation of system is carried out and the performance analysis is evaluated applying available PN methods and simulation tools. Finally, some preliminary concepts of further work are discussed.

1 INTRODUCTION

Business Process Modelling (BPM) is an important part of Business Process Management (BPMt). Several BPM languages are available on the market. Two of the most common ones are the extended —Event-Driven Process Chain (eEPC) and Business Process Management Notation (BPMN). The eEPC models should conform to certain rules structurally, should be coherent according to the functional (behavioral) aspects, and should be easy to simulate for the controlling and the analyzing of the system. There are some tools to support the verification and authentication of eEPC Models. However, these existing tools are not sufficient for behavioral analysis of the model and simulation purposes. The insufficiency of these tools stems from the semi-formal structure of the eEPC. In addition, eEPC represents only the static view of the structure of the process. These findings hold also for BPMN. However, in project based sectors like the construction industry, models must be dynamic and ready for the interchange. Transformation from semi-formal Business Process Models into Petri Nets (PN) is one possible method to verify these models with an exact syntax and semantics. PN is both a graphical and mathematical modelling language with a reach theory for analyzing the behavioral and structural properties. PN gives a high facility to the designers and managers to model the dynamic features of the system during design and to control the system during operation.

2 PROBLEM

In BPMt it is not easy to control a whole system without functional tool. In recent years there was an increase of research and development for this topic. There are five main phase of BPMt; Design, Modelling, Execution, Monitoring and Optimizing. Every phase is important for the system and BPMt well discriminate between them. BPMt in system and software engineering is the activity of representing processes of an enterprise, so that the current ("as is") process can be analyzed and improved in future ("to be"). BPMt is typically performed by business analysts and managers who are seeking to improve process efficiency and quality (Ko, Lee & Lee 2008). The process improvements identified by BPMt may or may not require Information Technology involvement, although it is a common driver for modelling business processes on creating a master process.

There are some tools in the industry to support the modelling of the system, like ARIS or BPMN based tools. All of them use some BPM languages, like EPC or BPMN. These tools can be applied for the construction processes too. However the construction industry needs more sophisticated facilities to design and to control inherent uncertainties of their systems. Therefore simulations are very important for this purpose. It is not so easy to model with BPM languages, which are semi-formal. Also the tools don't give any option to the users for the simulation. For the simulation and verification of these models, they must be transformed in

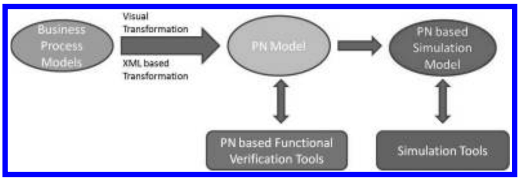

Figure 1. Suggested approach for PN based model verification and simulation of business processes.

appropriate simulation model which usually lead to some data losses. For the prevention of these losses, PN, which is a formal modelling language, can be applied. Therefore an approach is searched to verify and to simulate Business Process Models with minimum data loss. Our preferred approach is given in the Figure 1, which is an advanced version originally developed by (Raedts, 2008).

The transformation to the PN can be done with both a visual transformation methodology and XML. In this paper the visual transformation methodology is shown using already available transformation rules extended by some new ones. The transformation represented in XML is discussed on a conceptual level as a baseline for our further research.

3 BUSINESS PROCESS MODELLING

In the following we will consider two BPM methods namely; Event-driven Process Chain (EPC) and BPMN. EPC is a business process modelling language for the representation of temporal and logical dependencies of activities in a business process (Keller, Nüttgens & Scheer 1992). In another mean EPC is a BPM language and it provides comprehensive means for modelling the relevant aspects of a business processes (Loos & Allweyer 1998). The language is targeted to describe processes on the level of their business logic, not necessarily on the formal specification level and to be easy to understood and used by business people (van der Aalst 1999). The EPC method was developed at the Institute for Information systems (IWi) of the University of Saarland, Germany, in collaboration with SAP AG (Loos & Allweyer 1998).

The eEPC is the extended Event-driven Process Chain and, as the name implies, the eEPC method is the extension of EPC and is applied for the requirement definition phase of the control view. The eEPC method is more powerful than the EPC when business process modelling is considered, because the information objects of the data view, the organizational elements of the organizational view and the resources of the resource view are interlinked with the logistic view and can be shown precisely together with the functions of the function view and the events of the system status. These additional views increase the understanding and the clarity of the processes.

BPMN (Object Management Group 2006) is another widely used standard for Business Process Modelling, which provides a graphical language with Business Process Diagrams, which is based on flowchart, activity diagrams and UML techniques. It is easy to use and understand for both technical and non technical users. An overview about BPMN provides (Silver, 2009) for instance.

4 PETRI NETS

Petri Net (Murata 1989) is a well-accepted formalism for modelling concurrent and distributed systems in various application areas: Workflow management, embedded systems, production systems, and traffic control. It provides a uniform environment for modelling, formal analysis, and design of discrete event systems. The PN method, which was invented from Carl Adam Petri in 1962 (Petri 1962), is a graphical and mathematical modelling method applicable to many systems with a reach theory (such as Reachability Trees, Incidence Matrices, and Invariants Analysis) for analyzing behavioral (soundness, liveness, reachability, etc.) and structural properties of a system. PN provides both a graphical and mathematical modelling language, which gives a high facility to the designers and managers to model the dynamic features of the system during design and to control the system during operation. Also it provides analytical results with much of the modelling flexibility of simulation.

The primary difference between Petri nets and other modelling tools is the presence of tokens which are used to simulate dynamic, concurrent and asynchronous activities in a system.

There are two main types in the classification of PNs, which are Low Level PNs (simple nets) and High Level PNs. Low Level PNs are the basic graphical and mathematical representations of models without any extensions. But in the real life systems performance requirements are very important. For that reason several types of PNs (timed, colored, hierarchy, attributed, etc.) were developed, which can be used separately or combined with each other.

In project based sectors like the Construction Industry, models must be dynamic and ready for the interchange. Interactions between the elements of the construction process, and also concepts like resource sharing, documentation, cost reductions, etc. are very important issues, which has to be considered in the simulation. For that reason PN, which is a dynamic modelling method, can be used to verify semi-formal business models and to simulate construction process models.

5 TRANSFORMATION METHODOLOGY FROM BUSINESS MODELS TO PETRI NETS

For the transformation approach, already introduced in the Figure 1, the available methods are shown, existing gaps are identified and some of the transformation gaps are solved. (Fig. 2).

Event Driven Process Chain is a business modelling language, which is aimed to describe processes on the level of their business logic. It helps to easily understand business process for the business people but it does not define a formal specification level. Originally this was not a problem but with the upcoming request for extensions and specifications of the processes it causes a problem. Neither the syntax nor the semantic of an EPC is well defined. This fault will become manifest at least when there is real need to check EPCs for their consistency in order to control workflow systems (Langner, Schneider & Wehler 1997).

Transformation from EPC to PN is well developed by (Van der Aalst 1999) and from eEPC to Colored PN is given by (Oanea 2007). However there exist still gaps for extensions like input or output objects. Therefore transformation of objects from EPC to PN is extended by some new transformation rules as given in Figure 3. Extensions of EPC such as information objects, organizational units or resources are mapped into the PN Objects. In T1 the input and output information objects differ from each other, whereas in the transformation T2 they are the same.

The transformation from BPMN to PN is shown in Figure 4. In addition to the transformations from BPMN Objects to the Petri-net Module in (Dijkman, Dumas & Ouyang 2007), there are three new transformations developed (TR7, TR8, and TR9), which are shown in the Figure 4 for resource allocation, organizational units, information sharing, etc. The same reason in the eEPC holds for BPMN. There is a gap for the mapping of resource objects to PN.

The data object X is an input for the Task A in the transformation T7. For the transformation rule T8 the data object Y is given as an output of the

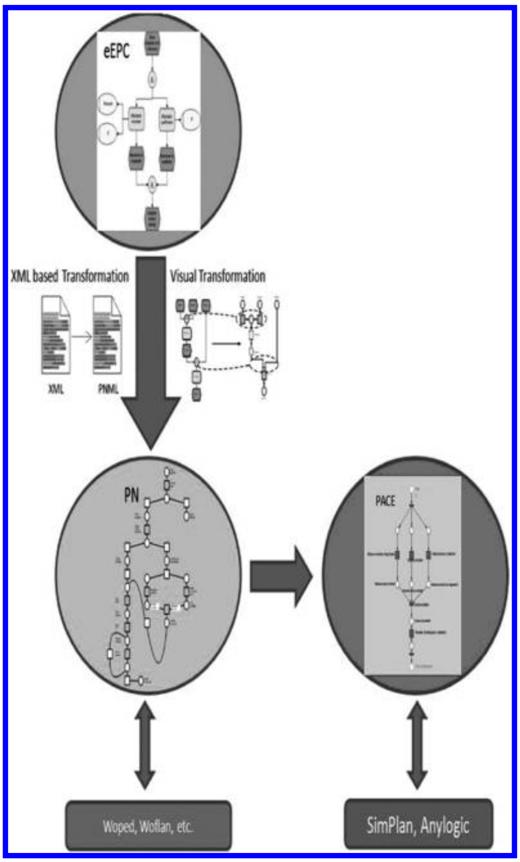

Figure 2. Methodology for transforming eEPC to PN (The same procedure holds for BPMN).

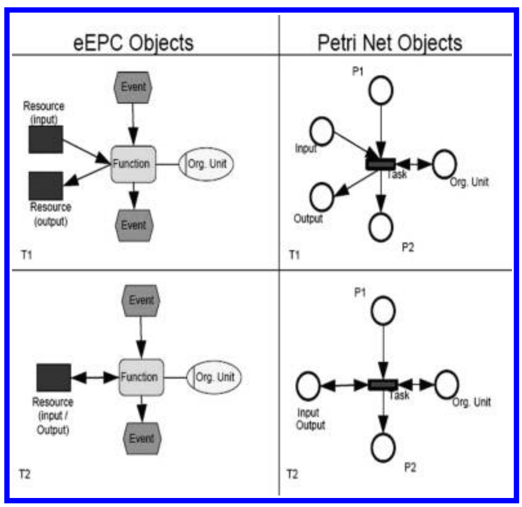

Figure 3. Pattern for mapping eEPC Objects to PN Objects.

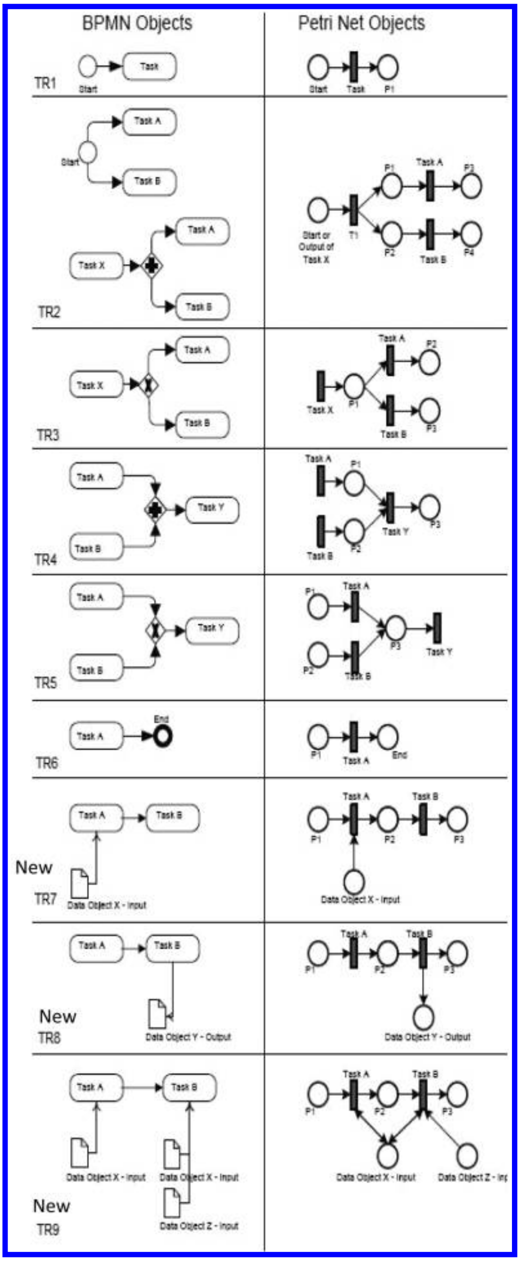

Figure 4. Pattern for mapping BPMN Objects to PN Objects. (Read: Data objects = Resources).

Task B. In the transformation TR9 there are both input (X) and output (X and Z) objects. The focus of the transformation TR9 is that the Data Object X may be a resource such as Crane or Digger, which is not consumed after use. Therefore it can be used in both tasks A and B.

6 BEHAVIOR ANALYSIS AND SIMULATION WITH PETRI NETS

After the transformed BPM into PN there is a possibility to analyze and understand their behavior in an objective way, because Petri Nets as a mathematical method possess a number of analysis properties. These properties help the system designers during the modelling phase to find the absence or presence of the model. There are two types of properties, which are very important namely behavioral and structural properties. The behavioral properties depend on the initial state, or marking of a PN. Structural properties depend on the topology and net structure of the PN (Zurawski & Zhou 1994). The main behavioral properties are reachability, boundness, safeness, conservativeness, soundness, etc. These are very important to verify Models.

Another important issue for the system designers is simulation. In manmade systems there is a requirement to know the system performance already during the design phase. PN has a formal syntax and semantic together with the graphical modelling attributes, hence PN is ideal to be used as a simulation model. There are several PN tool available to be used for modelling and simulating.

In BPMN there is not any information about the consumption or reuse of the resources. However in a PN model the user can define the resources with the information of consumption and reuse with one and the same object. In Figure 7 an instance model is shown, which is transformed from the eEPC model (Fig. 5) or BPMN model (Fig. 6) to PN model. The example is about concrete work with the resources crane, pump, formwork, reinforcement, concrete and workers. However the workflow is the same in PN as in the semi-formal business models, where every common resource is located at an input place.

In this example Low Level PN is used to construct the process model. Also High Level PNs can be used for more detailed and specialized process models. After the transformation of the business models to the PN, a common market tools can be used to verify the structure and behavior of the model. System deadlocks and other specifications can be identified with these tools like Woped and Woflan (Van der Aalst 2003). The Instance PN model is analyzed with Woped and Woflan. The reachability graph is obtained (Fig. 8) and sinks are found. Analysis is revealed that the model is not sound.

For the simulation purpose, the program PACE is used, well developed by (Eichenauer, 2007) showing several automations and a powerful Graphical User Interfaces (GUI). Many extensions (time,

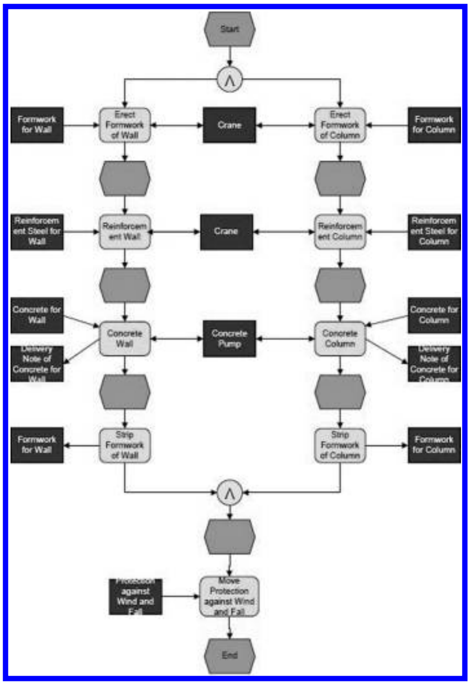

Figure 5. Instance model with eEPC.

Figure 6. Instance model with BPMN.

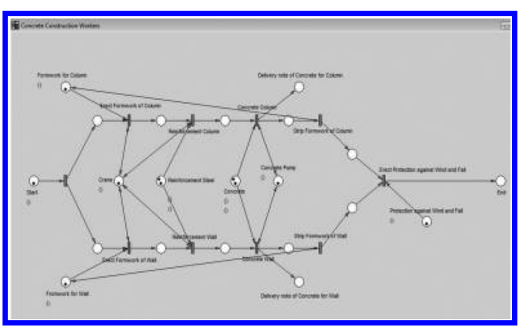

Figure 7. Instance model with Low Level PN.

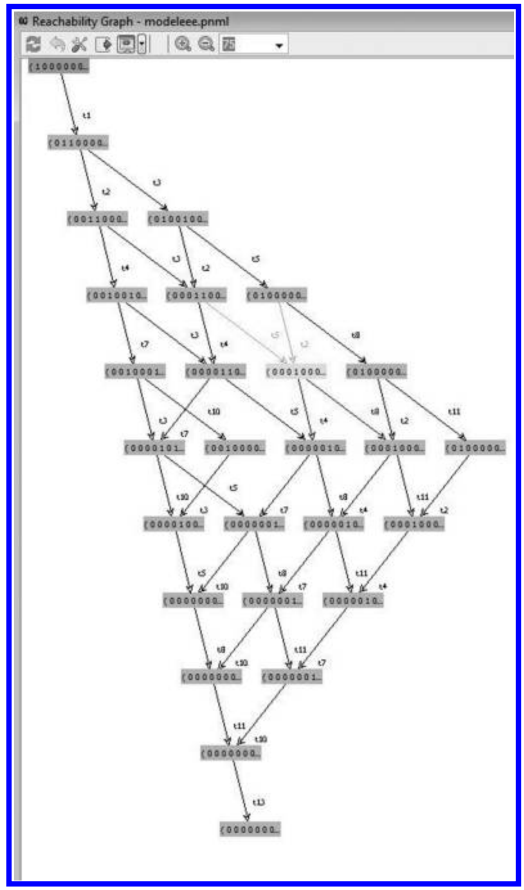

Figure 8. Reachability graph of instance PN model.

attributes, Boolean, etc.) of PNs can be used. The model can be checked during the operation and the system can be controlled with the GUI. The instance model in (Fig. 7) is developed by the PACE. But the special attributes of the program and the extensions of PN are not used in this Low Level PN example.

7 CONCLUSION

Construction processes are very complex. The general objectives of the project management are the optimisation of cost, time, and quality. For this purpose several methods were developed to model such systems. In this paper two of these methods are discussed and an appropriate approach for the semi-automatic set up of simulation has been developed. Low Level PN is selected as simulation method and transitions from eEPC and BPMN has been further developed. In further works, these transformations will be extended to High Level Petri Nets.

Transformation from Business Models to PN is shown in two ways. In this paper Visual transformation rules have been shown, whereas the transformation with XML has been shown on a conceptual level. Because of all considered BPMs have standardized Mark-up Languages (like languages BPEL for BPMN), XML has been selected as transformation language. In further works, automated transformation with generated XML codes will be envisaged.

PN was selected, because data losses are usually less compared to other modelling methods. PN gives excellent power to the managers to design, control, simulate and analyze the system. However for complex systems there are some limitations to be considered, such as computability, scalability, and to govern the modelling complexity. Therefore more advance simulation tools (like Simplan or Anylogic) are needed and already included in our suggested methodology. Some preliminary transformations from PN to these tools have been already developed, but not shown in paper. In our future work such transformations will be further developed and the research will be extended to highly automatic transformation methods.

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Application of process modelling for industrialised bottom-up production system in the BIM-integrated BC industry: Prototype of parking garage projects in The Netherlands

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ABSTRACT: With the active advent of BIM as an innovative driver for a paradigm shift in the BC industry, all relevant participants are facing new challenges. Especially, the general contractors are trying to transform their traditional production system into an industrialised system that is based on the prefabricated and modular product objects by using BIM. Similar to what other industries achieved by the successful mass customization production system, it is necessary for the BC industry to reengineer the production process in order to maximize productivity and to minimize losing value. BIM provides the solution to transformation of a mass customization production system by visualization in the very early phase of the production, by facilitating collaboration in the production system and by the accumulation of all reusable information in order to make it accessible. This paper explores some possibilities of the producer-positive bottom-up production in the BIM-integrated BC industry. Other industrialised cases and relevant literature are reviewed. The Systems Engineering approach is introduced as one of the most suitable underlying methodologies for the realization of a mass-customized production system in the BIM-integrated BC industry. By using the business process reengineering methodology, the paper proposes process models (IDEF0) for the general contractor to illustrate the processes such as how-to-develop, how-to-use, how-to-collaborate, and so on. Finally, a specific prototype using the proposed process modelling is introduced in order to evaluate the proposed system and to provide guidelines for further development. Findings of this research project are evaluated using the prototype of parking garage projects in the Netherlands.

1 INTRODUCTION

In the last decades, the BC industry has encountered in creasing demands from society and the clients for higher quality products, shorter lead-time, lower cost, etc. Buildings become ever more complex and are situated in over-crowded or complex environments. Great many research and development activities have been carried out in order to come up with solutions for increasing expectations from and needs of the BC industry. ICT (Information and Communication Technology) is regarded as one of the technologies offering key solutions within the construction business activity. Researchers, software developers, and construction practitioners have applied ICT-based solutions in order to automate different parts of the construction process in variety of ways. But unfortunately a lot of innovative approaches and ICT-based solutions in the BC industry have failed or fell short of delivering their expected outcome because the construction industry has a different nature when compared with the other industries (Ozsariyildiz 1998, Dado 2002, Kim 2009).

1.1 *Towards Building Information Modelling*

With the active advent of BIM (Building Information Modelling) as an innovative driver for a paradigm shift in the BC industry, all relevant participants are facing new challenges. With BIM, all types of accurate geometrical representation of building deliverables are expected to be basically available. Furthermore, it is the goal of BIM that all related information is more easily shared and reused. Better design services, better production quality and more customers' satisfaction are expected by BIM users. There are a lot of benefits anticipated in the BC industry as almost all BC industry participants eagerly plan to fully implement BIM (Azhar et al. 2007, Eastman et al. 2007).

As a matter of fact, BIM-applied construction projects reduce project delivery time up to 40% and estimation time by 7%, according to CIFE technical reports of Stanford University. These reports indicate that the cost estimation accuracy and clash detections are enhanced by the use of BIM (CIFE 2007).

But, a lot of collective efforts from all actors are needed in order to properly implement a complete BIM. Presently BIM is dramatically reshaping the way project teams work together. Also BIM has affected the system for efficient delivery of products within estimated budget and planned time.

Especially, SmartMarket Report on Building Information Modelling in 2008 expected contractors to see the greatest increase in BIM usage. Thirty eight percent would be heavy users, up from 23% in 2009. Only 12% expect light use of BIM, compared to 45% the previous year. Although general contractors report relatively limited BIM use compared to other disciplines such as architects and engineers group, they are quickly catching up. Currently 23% use BIM on 60% or more of projects (SmartMarket Report 2008). For general contractors, one of the most interesting benefits with BIM is the realization of industrialised or even semi-automated delivery system in the BC industry.

Therefore, general contractors are trying to transform their traditional production system into a more industrialised system based on the prefabricated and modular product objects using BIM. Similar to what other industries achieved by the successful mass customization production system, it is necessary for the BC industry to reengineer the production process in order to maximize productivity and to minimize losing value. BIM provides the solution to transformation of a mass customization production system by visualization in the very early phase of the production, by facilitating collaboration in the production system and by the accumulation of all reusable information in order to make it accessible.

1.2 *Revisited industrialised context*

Why is the concept of industrialization so important for the BC industry? In order to answer this question, first of all, the current state-of-art and future of the BC industry should be explored and understood in the general context of the technically innovative progress of human society over time. In this respect, Toffler (1980) identified three chronological classifications of the civilization establishing three technical waves. According to his book "The Third wave", the civilization can be divided into three major phases (Table 1).

We live in the third wave world, the so-called 'Information Age', which has tangibly commenced at the end of 20th century with significantly increasing capacity and competency of the IT (Information Technology). The common use of computers and the internet for sharing and developing ideas and processing and transmitting this information not only in their own industries but also in daily lives has lead to reach in good condition to the information revolution anticipated by Toffler. Now most of industries are starting to enjoy benefits of successful application of Information Technology beyond the bottleneck of industrialization.

Table 1. Toffler's table of civilizations.

	Civilization	Production system
The first wave	Agricultural Age thousands of year	Decentralized and self-sufficiency production No division between producer and consumer
The second wave	Industrial Age three hundred years	Mass production based on the specialization Division between producer and consumer
The third wave	Information Age In progress	Customized production system Integration between producer and consumer: so-called Pro-sumer

But, how is our BC industry faring? With the information technology, today's consumer markets are changing faster and consumers are more demanding than ever (Piller et al. 2004). Clients currently demand technically and socially complicated requirements from all concerned producers in the BC industry such as the architects, contractors, and so on. Furthermore, it has been broadly accepted in the BC industry that they can maximize output and profit by integrating the existing individual participants in the BC project delivery, as opposed to the traditionally fragmented trend (Matthews et al. 2005, Evboumwan et al. 1998). More importantly, although some information technologies have had a considerable positive effect and proven a possibility on the new way of working in the BC industry, its influence and future is still incomplete and moreover sometimes invisible or nothing at all. More fundamentally, why did the BC industry never make the quality jump by industrialising its own practice, like most of the other industries did? It is obvious that an industry did not change their traditional system with any urgency as business survival. This in turn raises the question why the BC industry has managed to survive so far without dramatic changes. Regarding this question, Cuperus (2007) interestingly and simply explains that "…there was never the need to change. Poor as well as affluent societies tend to sustain housing shortage, in which the BC industry has to deliver in a supply market, a market with no alternatives for buyers...“ Moreover, Warszawski (1999) pointed out the lack or absence of a sufficient industrialized base in the current BC industry. Actually, among several characteristics of industrialization such as mass production, standardization, offsite production and machine-made production, some has been more and less applied in many projects but others are still hardly applicable in practice. Particularly, even if off-site, machine-made production usually applies only to building components and materials, their end-deliverables are still manufactured or assembled on site by a lot of hand work with a relatively low degree of precision and with a high degree of building failures (Nederveen et al. 2009). Therefore, the BC industry looks like a more and less industrialised one, but it is still based on an invisible craftsmanship and unforeseen outsourcing-based industry, rather than a fully industrialised one with efficient and effective benefits.

In this regard, the current BC industry is just willing to enter the new Information Age without any complete basis of industrialization from the second wave. In this case, it would be obviously getting more complicated and more challenging to introduce and apply upcoming innovative Information Technology (IT) to the BC industry. In the past the BC industry has postponed to be properly industrialized under a nice excuse that ‘the BC industry is different from any other industries’. Therefore, if we are really impatient to catch up with the progress of the other industries such as the splendid achievements of IT and hence anticipating benefits from the automation concept, the first and most critical task would be to create an industrialized base. That is, the convincing groundwork on the industrialization in the BC industry is imperative to solve the research problem. That is why an attention has to be paid on this topic again.

2 CURRENT INDUSTRIALISATION IN THE BC INDUSTRY: TWO BUSINESS MODEL ANALYSIS

So far, a lot of trials for industrialized construction, most of which is modular housing project, have been made and some of their efforts have been launched in the market. But, so far they are struggling a lot to make an even-breaking profit. In this paper, two interesting business models in the market of industrialised BC industry are introduced and briefly analysed to extract the requirements for better industrialised process in the BC industry.

2.1 *BoKlok by IKEA and Skanska*

BoKlok concept and brand was initiated in the mid-1990s. At a building exhibition in 1993 in Karlaskrona, Sweden, an IKEA team designed a compact living house to meet the requirements of common people such as affordable price, green area, and so on. This resulted in a two-storey wing house with 3 apartments that became a pilot project of the BoKlok home. In 2001, the project was analyzed for a feasibility study on a real business case. The collaboration of the two companies, IKEA (A world leading furniture manufacturer) and Skanska (A world leading construction firm) was intended to provide low-budget housing by sharing amply accumulated knowledge from their own business experiences. For this purpose, they established a new joint venture (private and limited company), BoKlok, by owning fifty percent of shares each. Most of factories for the production are run by themselves in Sweden and some parts of buildings are outsourced on collaboration with Moelven (Modules Building). Their business area has been extended to Norway (2002), Finland and Denmark (2003), and to the UK (2006). One of the most valuable strengths of this venture that the business model of BoKlok is based on a lot of tactical knowledge from the IKEA concept on systematic component production and a lot of experience from Skanska on constructability and construction project delivery. This is a win-win strategy for both companies by opening new markets. Still, uncertainty and weakness of their collaboration relation is one of the internal weaknesses. Furthermore, too specific target group, particular at cheap housing, would lead to limit on extending their business to other types of industrialised construction projects. Also the limited flexibility in their solutions should be improved in the near future.

2.2 *Corus Living Solutions by corus*

Corus Living Solutions established in 2003 provide fully fitted steel-framed modules, which are designed and manufactured at its Shotton Works in North Wales and delivered to the construction site as ready for assembly building blocks. The vision of Corus Living Solutions derives from their belief that an off-site manufacturing system like Corus Living Solutions can offer our society cheaper, faster and better houses, resulting in fewer faults, and reduced waste and less transportation cost. A strategic intent of Corus Living Solutions is to become the lowest cost manufacturer of modular buildings. The feasibility and sustainability of their business model have been proven successful when they already achieved 5000th modules of sales in the beginning of 2009 without any lost time injury. Their main target facilities are the accommodation facilities such as Defence Estates, Hotel chains, Halls of residence and hostels and Key worker and specialist accommodation, meeting the immediate and anticipated demand for high quality, functional and innovative accommodation (Storgaard 2009). Corus Living Solutions run their business with a 'No faults forward' philosophy, which leads to a right-first-time operation. This idea is enabled by having the right skills in the right areas within a robust quality assurance process. And they highly take into account of reducing risks and hazards associated with traditional onsite construction. For this purpose, a joint venture was formed between Corus group in metal production industry and two contractors in the construction industry (Mowlem and KBR). This business case shows a well-planned forward integration strategy based on material (Metal) background. They have already received enough orders from specific construction companies to stimulate a sustainable development. Annual production capacity is reached up to 3000 units including MOD living quarters and student halls, etc. Furthermore, comparing to other industrial housing businesses, Corus are also preparing the different types of construction project such as Modular Rail Platforms system and BI-Steel. But, a limitation of design flexibility is addressed; particularly container-box unit design limits their possible market.

3 INDUSTRIALISED PROCESS IN THE BC INDUSTRY

3.1 *Bottom-up process: Another possibility with BIM*

The current BC industry is client-oriented. A group of clients including users, stakeholders and even their consultants like architects usually initiate projects in the BC industry market. The suppliers start their work with a detailed design and works from there. According Nederveen et al. (2009), this traditional way of working can be called a client-driven building process. The integrated project delivery methods such as Design-Build, BOT, etc. are recently and commonly used, but a tendency of the client orientation still has a strong position. But, unfortunately, they do not have enough knowledge and experience about construction the way they are knowledgeable about the engine system or certain components when buying a car. Definitely, producers like general contractors can acknowledge this. Clients easily change their mind as time goes by and their products are somehow visualized virtually or even physically. For this reason, we lose a lot of visible or invisible value from fixed processes without ample use of producer's knowledge and expertise. Therefore, this inefficient and fixed system should be changed. A better idea

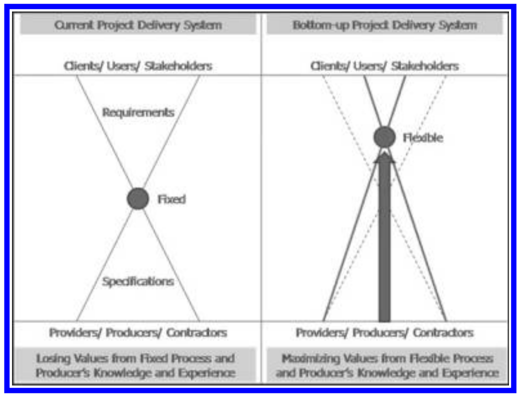

Figure 1. The bottom-up project delivery system.

is that a group of producers actively provide their specification like the other industries make a successful progress on their production system. Arguably a flexible coupling point between the clients and producers in a bottom-up approach in the BC industry is necessary as shown in Figure 1.

Nederveen & Gielingh (2009) pointed out the very similar approach; " … A 'supplier-driven' industrial process has a number of advantages. First of all, it is possible to develop a proposal in a very short time by combining and assembling the standard parts of the existing building system. This can be done by using a parametric design system in which all standard parts and connections of the building system are stored, as well as design and construction knowledge associated with the parts and connections. Moreover, it is possible to gain insight into the consequences of the design proposal in a very short time, in terms of production and maintenance cost, but also in terms of environment impacts, etc. Finally, a significant advantage is the possibility of a controlled industrial construction process, with potentially a much higher degree of precision, performance predictability and lower number of construction failures … " In this paper, Bottom-up approach (which means more supplier-driven project delivery system in the BC industry) is presented to achieve a better, more appropriate and full industrialisation.

3.2 *Systems Engineering process*

Systems Engineering is the methodology used to acquire and execute projects in a standardized way using a structured method that guarantees that one gets what one is asked for as well as establishing a relationship between the problem (requirements) and the solution (designs). It includes all aspects that play a role in the projects life cycle ensuring that clear design choices are made (Ballast Nedam 2009). The Dutch European construction clients have been asking the construction contractors to apply SE functionality to their project for maximizing the achievable efficiency in design and construction process and leading to the advanced synergy. (RWS, 2010)

Figure 2 shows that the process flow of Systems Engineering could be depicted as "The integrated V-model" with a descending line representing the further detailing of the specification and design process and an ascending line representing the production process. Also, it could be described as the construction project life-cycle combining the V-models of the SE (Figure 2). This refers to the firm supposition that the V-model of SE could be considered not only in the whole project life-cycle but also in any specific phase of the construction project. Depending on the level of the V-model, the definition of terms such as requirements or systems could be differentiated. At least in the BC market of the Netherlands, the clients including governmental developers are more and more asking for the Systems Engineering process in order to achieve their expectations. Some leading general contractors such as Ballast Nedam in the Netherlands often use Systems Architecture to meet this tendency, track clients' requirements and more efficiently carrying out their projects. In the viewpoint of the modeller, the Systems Architecture is a kind of conceptual modelling. Especially, xBS such as System Breakdown Structure, Work Breakdown Structure and Requirement Breakdown Structure is one of the most commonly used types of Systems Architecture.

Nederveen & Gielingh (2009) in their previous research put an emphasis on the following: "… Part of this industrial design process is already supported by existing tools and technologies. Part libraries are already around for decades; parametric design systems are also around for many years. But

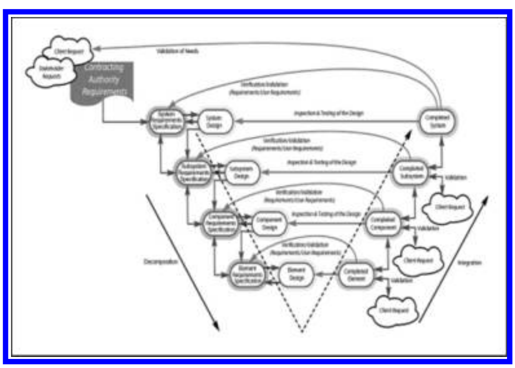

Figure 2. Systems Engineering V-model (Source: RWS Guide-line Systems Engineering for the Dutch public works and water management, 2010).

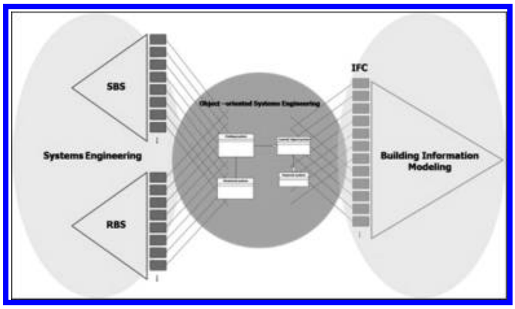

Figure 3. Integrated system structure.

a complete system for configurable design based on IFCs does not exist yet. Difficult parts are for example: the link between IFC-models and library structures, the link between library elements and functions and algorithms that can find matches and the extension of product libraries with building knowledge of all kinds …"

In this regard, Systems Engineering approach provides more structured library elements and functions with the currently limited-used BIM. As Figure 3 shows (focusing mainly on the 'Information structure'), an integrator between SE and BIM is necessary to propose the new industrialised project delivery system. The proposed system should be not only individually modelled by product modelling and process modelling methods but also integrated by means of process to product modelling such as GTPPM (Georgia Tech Process to Product modelling), which is developed by G. Lee together with C. Eastman and R. Sacks, which is based on the methodology of 'process to product modelling' (Lee 2003). In this paper, only process modelling part is discussed.

3.3 *Business Process Reengineering*

In practice, the most critical problem is not the absence of enabling technologies or methodologies but the fragmented application of them. Nederveen et al. (2009) pointed out that all enabling technologies such as parametric design, building information modelling, cost calculation and industrial production are already available but a vital factor for realization of full industrialisation in the BC industry is an integration of them since any synergy as well as efficiency is never anticipated in the current fragmented applications. Furthermore, they put an emphasis on that it is more important that an innovative business model is developed and introduced that is based on the concept of "supplier-driven demand". This means the bottom-up approach described in this paper. In this regards, this paper argues that BIM and SE should be revisited as enabling technologies for industrialisation of the BC industry. More importantly, the process should be reengineered in order to be well integrated in the business models of the industrialised BC industry.

According to Hammer & Champy (1993), Business Process Reengineering (BPR) is the fundamental rethinking and radical redesign of business processes to achieve dramatic improvements in critical, contemporary measures of performance, such as cost, quality, service, and speed. Since BPR provides the fundamental rethinking and redesign for dramatic improvements, it is imperative for the BC industry to transform their traditional project delivery system to an industrialised system. One of the tools for BPR is a process mapping or operational method study (O'neill & Sohal 1999). These concepts have been incorporated into specified tools such as IDEF0 (Yu & Wright 1997). IDEF0 process modelling in this paper is generated for Business Process Reengineering to be reshaped to an industrialised bottom-up project delivery system by integrating Systems Engineering into the BIM. It can provide a well-visualized means for modelling the functions, relationships and data required by an information system or business process (Dorador et al. 2000). An IDEF0 model is composed of a hierarchical series of diagrams that display increasing levels of detail describing functions and their interfaces within the context of a system (NIST 1993).

4 PROCESS PROTOTYPE OF MODULAR PARKING GARAGE SYSTEM IN THE NETHERLANDS

4.1 *Modular Parking Garage System*

Modular Parking Garage System in the Netherlands is a unique and innovative business model for a modular facility built mainly from prefabricated components (www.modupark.nl). Some companies in the BC industry raised the question of where travellers and staffs are parking their vehicles during the construction phase of their running projects. This simple question was a starting point for developing the new business model for delivering a temporary and re-usable parking garage. Ballast Nedam, which is a multidisciplinary Dutch property and infrastructure construction group offering a wide range of construction-related products and services, is not only strong in the precast concrete for a modular facilities but also is a leading general contractor in the Netherlands that has accumulated a lot of experience and knowledge in the project management such as financial engineering and contracting (www.ballast-nedam.nl). Business target and goal of the Modular Parking Garage System is to deliver a temporary or permanent modular parking garage using standard components such as HE steel and TT-Beam in order to quickly assemble, reuse and disassemble. Information and collaboration between disciplines and stakeholders for a modular parking garage can be efficiently managed by using BIM since parametric and object-oriented data of BIM in the supply chain management covering whole life-cycle are tracked and reused. Moreover, BIM can be used to efficiently and quickly generate the first visualized draft of the modular parking garage based on a number of choices. Also BIM takes into account offering other possibilities such as quantities take-off, cost analysis, structural analysis etc. For this purpose, BIM has been actively introduced and applied to this business in practice.

4.2 *Purpose, viewpoint and scope of IDEF0 modelling*

The purpose of process modelling by means of IDEF0 is to analyze the current process in Modular Parking Garage System as one of the industrialized construction projects and to come up with a better process by integrating Systems Engineering and BIM. Especially, Business Process Reengineering is intended to be reshaped to an industrial and supplier-driven business model by means of a comparison between AS-IS and TO-BE IDEF0 diagrams. The viewpoint is the information flow. It means that input and output are a variety of types of all relevant information from certain information systems, software applications, etc. Mechanism and Control parts in the following IDEF0 modelling are also something related to information. Finally, the scope of IDEF0 modelling is the design phase of entire life cycle of the project. Actually, life cycle management of all relevant information is one of the main reasons why Systems Engineering should be integrated with BIM in the industrialised BC industry. More efforts for further research are necessary for other phases in the whole life cycle of the industrialised built deliverables. Therefore, this paper presents IDEF0 process modelling as a means for better information processing of an industrialised and bottom-up project delivery system, tackling with only the design phase.

4.3 *AS-IS IDEF0 process modelling*

Figure 4 (IDEF0 diagram A-0), an AS-IS model, shows input information for Modular Parking Garage System, its initial requirements and constraints for the modular parking garage system, which are received from clients and delivered to

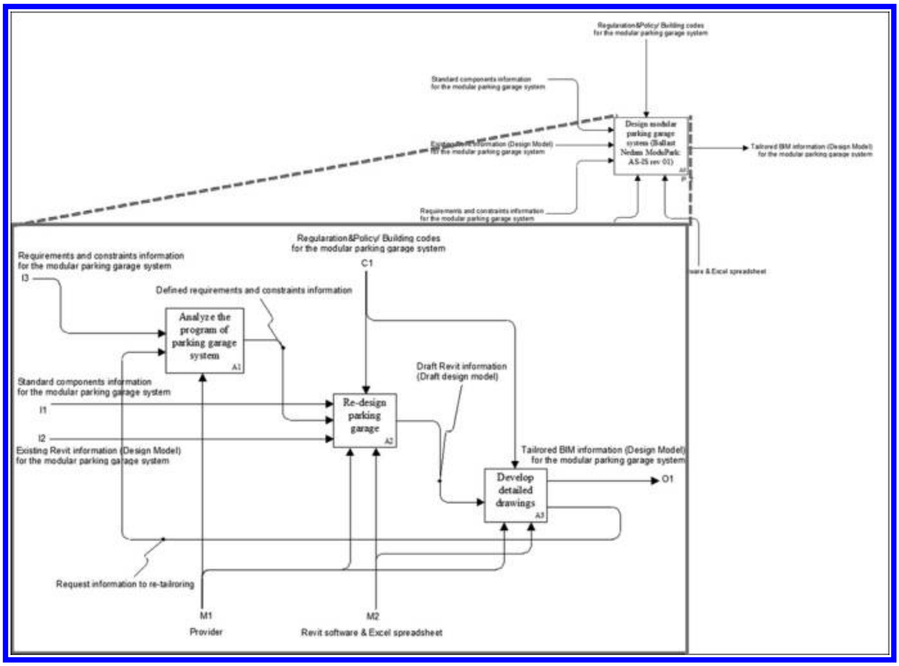

Figure 4. AS-IS process modelling for Modular Parking Garage System (A-0 and A0).

the design team in Ballast Nedam. One of the interesting information is to input some existing design models, which in this case are some product models of parking garage projects already generated by Revit Structure 2010. That is, they are re-used to design a parking garage system by re-tailoring with the clients' requirements and constraints. But, this process is still manually done. Also, the information of available standard components and materials are imported for the modular parking garage system. To sum up with input, the 3D modeller will re-design the existing Revit model based on standard components by taking into account clients' requirements and context. The design phase for the current Modular Parking Garage System is processed by two mechanisms which are designers and some software applications. In addition, regulations, policies and building codes control the design model.

In A0 diagram that is one-step more detailed. The design phase for the current Modular Parking Garage System is illustrated and specified by three activities. The first activity is to analyze the program of the parking garage system in the client's context. The next step is to re-design a modular parking garage system based on three information inputs which are 1) defined requirements and constraints, 2) standard components and materials and 3) existing Revit design model. Throughout this process, a draft Revit design model is produced. Two output options of the last activities with this draft are 1) tailored BIM (in this case, by Revit Structure 2010) the design model by developing detailed drawings or 2) the feedback for re-tailoring design model. Actually, these processes are iterative with a feedback loop. The most attention-grabbing finding in the AS-IS IDEF0 modelling is that the current Modular Parking Garage System is not that much different with the traditional fragmented, iterative and inefficient project delivery system. They use 3D design model by Revit Structure 2010. But, the use of BIM is limited in spite of containing more enabling competencies and functions even in a software application such as Revit Structure. Therefore, more supplier-driven approach to BIM, discussed in chapter 3, is necessary and Systems Engineering provides a more clear information structure to manage the entire project life cycle. Next chapter presents TO-BE IDEF0 model based on these findings in chapter 3 and AS-IS IDEF0 modelling.

4.4 *TO-BE IDEF0 process modelling*

The IDEF0 model of Figure 5 illustrates a reengineered business process model to propose the TO-BE situation for Modular Parking Garage System. In this Diagram main differences are shown in red. In input information, xBSs such as SBS, WBS and RBS which are different aspects of systems architecture in the process of Systems Engineering

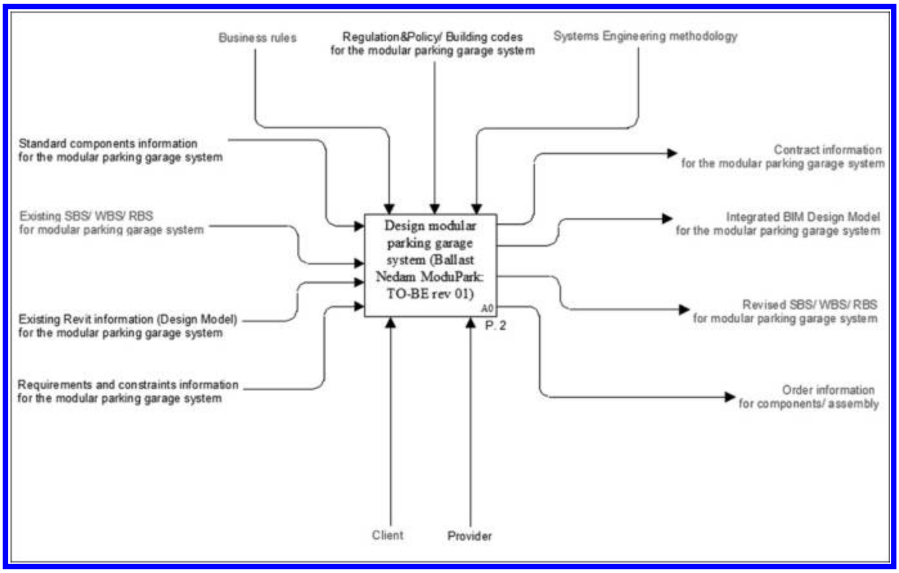

Figure 5. TO-BE process modelling for Modular Parking Garage System (A-0).

are imported to the design phase. The client as one of the mechanisms is called in during the design phase in order to ensure more clients' involvement. The clients' involvement should be limited by certain process to provide the initial requirement data as parameters and make a contract within the integrated system and but it is critically necessary for better supplier-driven project delivery system to make a clear distinction between clients' and suppliers' responsibilities. Therefore, the proposed design process starts with inputs from existing information for Systems Engineering and Building Information Modelling and is controlled by both the provider (in this case, designers and relevant employees in Ballast Nedam) and the client. Finally the system produces 1) contract information, 2) Integrated BIM design model as an implementation modelling, 3) Systems architecture as a conceptual modelling, and 4) Order information for components and assembly. The A0 and A2 IDEF0 diagram (Figure 6) illustrates the proposed system in more detail.

A0 diagram in TO-BE IDEF0 modelling consists of four processes, 1) Filling in the parameter sheet by client himself or herself, 2) Using integrated system (SE+BIM), 3) Making a contract between the client and the provider and finally 4) specifying the final specification of components and assembly. The most interesting and important thing is the integrated system itself. As seen in the diagram, this integrated system (SE + BIM or even more later on) can automatically produce a design solution, based on the input requirements by parameters sheet. Therefore, the requirement-based parametric design method is imperative for the realisation of the integrated system in practice (These issues are dealt with in the MSc thesis of the first author). As mentioned earlier, since this paper focuses on information processing, more detailed processes are depicted in the IDFE diagram A2 (the red box in Figure 6).

A2 diagram in TO-BE IDEF0 modelling consists of three activities, 1) Tailoring Revit design model by parametric design system, 2) Revising integrator (in this paper, UML modelling for Modular Parking Garage System) and 3) Generating all relevant information from SE + BIM integrated system. First step starts with the input data for parametric design and the existing Revit design model in order to re-use and standardise components information (the AS-IS process model). In the first step, the tailored Revit design model is sent to the proposed integrated system. Second step is to revise Integrator for SE approach and BIM application (Regarding Integrator, see more in chapter 3–2). At this stage, three inputs exist, namely 1) SBS/ WBS/ RBS, 2) Revit design information and 3) revised integrator itself. The information is integrated into one managing system, called the integrated system (SE + BIM). All relevant and required information is finally generated and delivered to the next step. The fascinating issue in all these processes of the A2 diagram is automatically conducted by a pre-defined and integrated system. In this paper, only two main promising concepts in the current BC industry, which are Systems Engineering methodology and BIM technology, are considered to propose this system but other available technologies and enabling

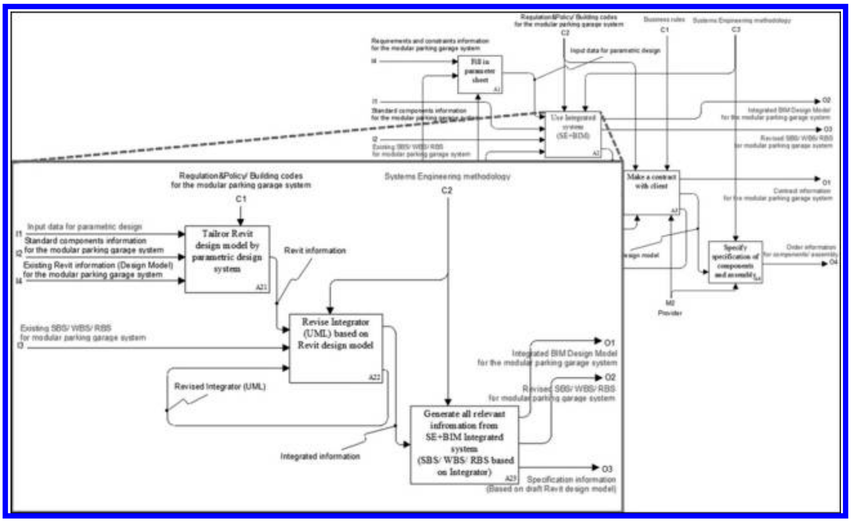

Figure 6. TO-BE process modelling for Modular Parking Garage System (A0 and A2).

methodologies can also be integrated in the future. This will be discussed in the further research.

5 CONCLUSIONS

5.1 *Findings*

This paper revisited an industrialisation context in the BC industry since industrial building has not yet become a mainstream development, in spite of a lot of trials and obvious advantages. With the active advent of BIM, all associated participants are more anticipating to transform the traditionally fragmented and craft-based project delivery system into an innovative industrialised system, which is based on prefabricated and modular product objects and components, similar to what other industries had already achieved. Based on a review of relevant literature, the reason is sought for why an industrialised approach has not that successful or even it has failed in the BC industry. More specifically, two real business models that are BoKlok by IKEA & Skanska and Corus Living Solution were analyzed with their limitations and strengths. Some requirements derived from chapter 1 and 2 were presented in chapter 3, which are based on a bottom-up process integrating BIM, Systems Engineering and Business Process Reengineering. By process prototyping of the Modular Parking Garage System in the Netherlands, the new industrialised process mainly proposed in chapter 3 was evaluated.

5.2 *Practical implications*

This paper proposed a new project delivery system for the industrialised BC industry. In this industrialised system that is based on a bottom-up process (supplier-driven) and Systems Engineering approach, a specific process prototype is developed by conducting Business Process Reengineering by means of IDEF0 modelling. The Modular Parking Garage System in the Netherlands is very unique and promising but it is necessary to be more properly and fully supported by BIM as well as applying the Systems Engineering approach in the project life cycle. Limited use of BIM and the absence of SE applications due to the traditional project delivery system were identified in the AS-IS IDEF0 process modelling. In the TO-BE modelling, these pitfalls were overcome by proposing the integrated system.

5.3 *Further research*

This paper opens discussion for several further research topics. In general, four research topics can be considered:

1. More detailed level of IDEF0 modelling is necessary to underpin this paper. Although the IDEF0 modelling in this paper is based on the analysis some existing in-house documents and views of the involved employees for the Modular Parking Garage System in Ballast Nedam, detailed levels are missing. More detailed IDEF0 modelling based on more data is essential for the business model to realise this industrialised approach in practice.
2. This paper focuses on the design phase in the whole life cycle of industrialised project deliverables. With the Systems Engineering approach discussed in chapter 3, the entire life

cycle management is available. Especially, xBS technologies such as SBS (Systems Breakdown Structures) and WBS (Work Breakdown Structures) are enabled in order to integrate all relevant information in the whole project life cycle. Based on this paper, other phases such as the construction phase or the maintenance phase could be discussed.

3. Modelling methodologies can be broadly divided into the "Product-oriented" and the "Process-oriented" modelling. This paper presented only the outcomes of the process modelling part of this ongoing research. The product modelling part is not that much tackled in this paper and is just mentioned as input, output and functions of the IDEF0 process modelling in the paper. Further research will attempt to make up for the product modelling part.
4. Other approaches and methodologies for industrialisation of construction should be introduced and integrated. This paper introduced only two enabling concepts, which are BIM and SE, as necessary technologies for the realization of industrialisation in the BC industry. According to van Nederveen et al. (2009), more available technologies such as parametric design, configuration management, functional design etc in the current BC industry should be imperatively integrated step-by-step into one industrialised delivery system.

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About the mapping problem of process to simulation models

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ABSTRACT: Using simulations for construction projects is still limited compared to other branches of industry like mass production in factories. The main reasons are the complexity of construction projects, the high expense and the long time needed to create a simulation model for each project and in addition to each objective asked for. A faster set up should possible if we could start from a formalised business process model. Business process models have been used widely to describe the logic, needed resources, and details of each single operation. This contribution presents preliminary research efforts about the transformation of business process models of construction projects to simulation models. The main focus is on the identification of mapping problem between typical business process patterns to simulation model patterns. This is studied on the hand of two simulations methods, namely discrete event simulation and Petri nets and three software implementations showing different object modelling data structures and frameworks as given constrains.

1 INTRODUCTION

Construction simulations are an effective instrument to gain preliminary information about construction processes. They can be very useful to minimise risk and/or increase efficiency in cases when ambiguities in process design are encountered, when resource supply/demand is accompanied by planning uncertainty, when material storage and equipment use cannot be planned in detail in advance and so on. In conventional approaches the development of simulation models is very time-consuming and therefore rarely used. Semiautomatic derivation of the simulation design from the construction processes would lead to a more frequently employment of this method. The knowledge gained by the simulation could be returned to the design phase of construction processes, e.g. in form of higher level performance indicators, or aggregate processes with higher certainty, to reduce ambiguity and improve process quality.

In the frame of the Mefisto project (Scherer 2010a) we are following the approach of a process-centred information framework, i.e. a simulation model is going to be deduced from the business process model (Fig. 1). The basis of this derivation is a formal or at least semi-formal described process model. In general processes are chronological and logical sequences of activities necessary for processing economically relevant objects (Becker & Schütte 2004). The conceptual specification of states and state changes is carried out by means of so-called-process models.

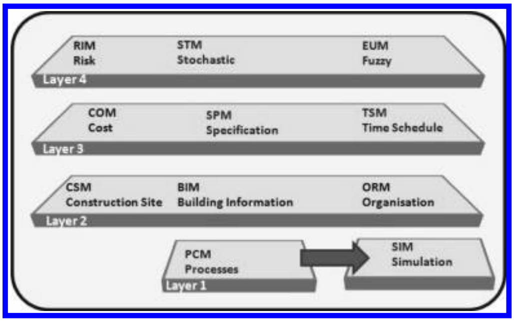


Figure 1. Process-centric multi-model space of the Mefisto framework.

These can represent tasks like planning, execution, coordination and controlling as well as material transport and transformation processes. In general the planning of sequences and the timing of the process activities are the central subjects of process modelling. For the purpose of business process modelling these process models can also be used to specify the respective business context of individual sub-processes, i.e. to depict the created and used informational and material business objects (integrated process modelling). Construction processes refer to all informational and physical processes which are directly and indirectly required to create the structure.

In construction practice the process modelling is currently used mainly for scheduling. Anyhow basic logical dependencies and available resources are only considered rarely and integrated models of construction processes including any necessary production resources and production results are only infrequently created. In the multi-model space of the Mefisto platform the model of construction processes takes a central role (Scherer et al. 2010b).

In the process-centric approach followed here the process model links the project relevant information sources, whereby the continuously use of specialist information in the model-based planning, simulation, and monitoring of the construction is possible.

2 PROCESS MODELS USING BPMN

As graphical representation of the construction process models the Business Process Modelling Notation (BPMN) was chosen (OMG 2009). The basic element of the BPMN modelling is the Task which represents a single process step and is symbolized by a rounded rectangle. The order of Tasks is described by the Sequence Flow, a simple solid arrow. In order to assign the Tasks to their operator or the process owner so-called Pools are defined which can be further divided into Lanes. A Pool would be, for example, a company whereas the Lanes represent different departments. The Tasks of different pools, however, are not connected by a Sequence Flow, but communicate over information flows. Besides the previously mentioned flow objects exists the so-called artifacts (Data Objects, Groups and Annotations) that do not affect the Sequence Flow or Message Flow of the Process directly, but provide information in any form. The most important ones are the Data Objects that assign documents, data, and other objects via undirected Associations or classify resources as an input or output of a task using directed Associations. For branching process flows Gateways are used to split up and merge the Sequence Flow. These Gateways serve as logical connectors. The basic forms are the Inclusive, Exclusive and the Parallel Gateway. Every so described process begins with a Start Event and finishes with an End Event. These processes are modularised as an assembly of business process objects in another research branch of the Mefisto project (Rybenko et al. 2010).

3 CASE EXAMPLE

The transformation of the construction processes discussed in the following sections is illustrated with the help of the example represented in BPMN notation in Figure 2. The sample process is based on a larger example that describes the creation of the floor of a high-rise building. From this the parallel construction of a column and a wall of reinforced concrete and the subsequent moving of the protection of the wind and fall protection were taken out.

After the Start Event the parallel sub-processes of constructing the column and constructing the wall are in principle similar. Both task sequences consist of “Erect Formwork of Buildings Element”, “Reinforce Buildings Element”, “Concrete Buildings Element” and “Strip Formwork of Buildings Element”. After finishing both sequences a merging Parallel Gateway determines that both sub-processes have to be completed to start the next task. This describes that the work on the elements of one level of the high-rise building has to be completed before the protections against wind and fall can be moved to the next level. After that the finish of the examined example process is marked by an End Event.

From the BPMN representation in Figure 2 it is apparent that the necessary informational and material resources to execute a task are assigned in the form of Data Objects. For example “Concrete Column” requires the concrete and, in case of concreting with a concrete pump, the object

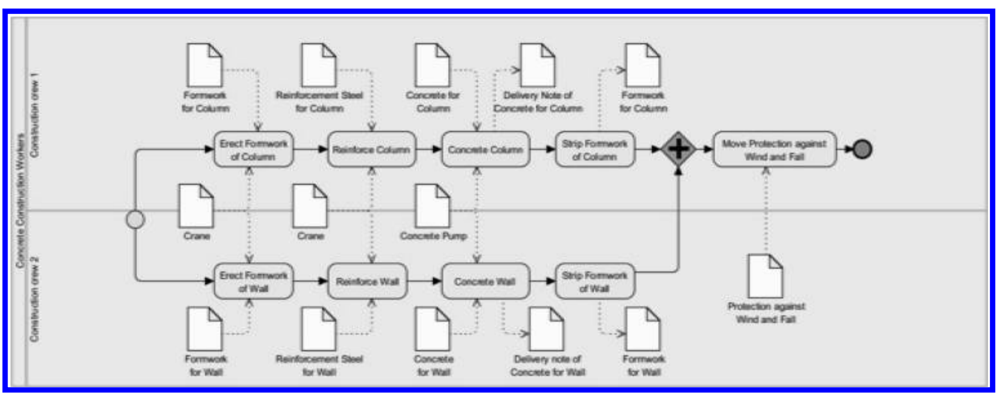


Figure 2. BPMN modelling of a floor erection.

pump. It produces the Data Object "Delivery Note of Concrete for Column". Usage of only one crane element implicates that both, the formwork of the wall and the column such as the reinforcement can be installed with the same crane.

4 TRANSFORMATION PROCESS MODEL DATA TO A SIMULATION MODEL

4.1 *Transformation to AnyLogic*

The simulation framework AnyLogic supports all the most common simulation methodologies in place today (http://www.xjtek.com): System Dynamics, Process-centric (Discrete Event), and Agent Based modelling.

It employs Java as its language for complex data structure definition, algorithms, and external connectivity. If needed, the modeller can extend the functionality of AnyLogic graphical constructs with pieces of Java code, which provides virtually unlimited flexibility. In face of the uniqueness of this transformation it is necessary to create the simulation model in very short time related to standard industry. Unfortunately there are no module libraries for higher simulations level provided. To use AnyLogic anyway, it is necessary to develop a module library for construction industry. This library should contain typically tasks for the simulation of a construction site like erection of columns or concreting of a slab. These tasks or simple objects can be grouped to simple modules. They should be designed in a way that they

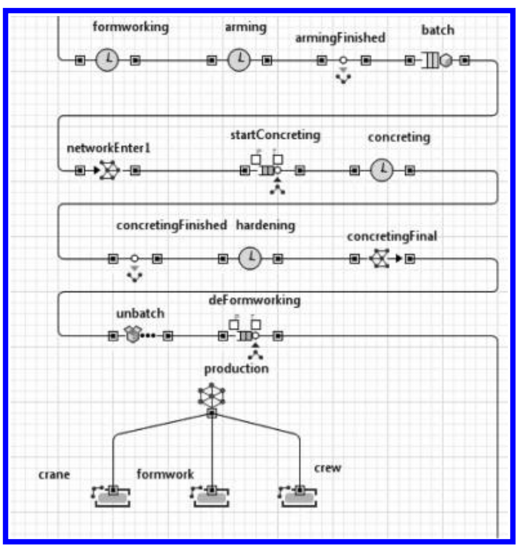


Figure 3. Simulation model with AnyLogic of the case example.

are combinable to larger complex modules. These complex modules should be again combinable to larger complex modules. Hence modules are to be organised in a hierarchical class structure. For instantiated simulation tasks and modules additional, problem specific information are necessary. This information will be acquired from the Mefisto information framework with the aid of the projectontology (Scherer et al. 2010). However the formalised business process model cannot straight forward transformed into to a simulations model. The kind of modelling is just too different.

The two basic concept of simulation are time and resources. Time consuming is normally modelled as a *Delay*task in AnyLogic Event Discrete Modelling. (Table 1) This leads to a reduction of many different simple process modules to only one and the same type of simulation task. To create from completely different simple process modules the task *Delay* is a n:1 object mapping and means, that only the attributes of this task, especially the time value and function, stamps the difference. To carry out this manually is possible but very inefficient, because too time consuming. Predefined transformations for frequently used construction processes would speed up the simulation model creation. Resources usage is formally modelled in most cases by the *Seize* of a resource and *Release* of a resource.

The resources are usually stored in a *Resource Pool* and not preattached to a single task or module. Hence they are available for all tasks and are used by them on demand. For logistic transportation, such as transportation of prefabricated elements from the fabric to the construction site, the combined *Pickup* and *Dropoff* tasks are available

Production processes, which combine different building materials, like the production of a concrete structural element, can be modelled as an *Assemble*task. In this task up to five building materials from different sources can be assembled to one new structural element. Suitable for simultaneous production, e.g. concreting two columns at the same time, are the tasks *Batch/Unbatch* or *Match*. In the Batch task a number of entities is batched together and can then processes together and later unbatched. The *Match* task waits until two entities are ready and release them together for further production. Not all work at the construction works is continuous, but unfortunately often the works accumulate. To simulate this, the *Queue* task can be used. Incoming objects waiting in the queue until the next task can process them.

In some cases it is advantageous not only to apply the discrete-event simulation. The advantage of the holistic AnyLogic is that, that arbitrary tasks can be simulated in an agent sub simulation. They are moved with the task *Enter* and *Exit* to or from the simulation.

Table 1. Mapping table for process to anylogic discrete event simulation.

BPMN Process Object	Anylogic Object	Description of Anylogic Object
Start Event	Source	Generates entities. Is usually a starting point of a process model.
End Event	Sink	Disposes entities. Is usually an end point in a process model.
AND Gateway	Match	Synchronizes two streams of entities by matching pairs according to a given criteria
	Assembler	The object allows certain number of entities from several sources (5 or less) to be joined into a single entity.
Resource Usage	Resource Pool	Defines a set of resource units that can be seized and released by entities.
	Seize	Seizes a given number of resource units from a given Resource Pool
	Release	Releases a given number of resource units.
	Service	Seizes a given number of resource units, delays the entity, and releases the seized units.
Transport Task	Conveyor	Moves the entities along a path at a given speed.
Produce something together	Batch	Converts a number of entities into one entity
	Unbatch	Extracts all entities contained in the incoming entity
Simple Task	Delay	Delays entities for a given amount of time.

4.2 *Transformation to plant simulation*

Plant Simulation from Siemens (Tecnomatix)is a well-known discrete event simulation tool. It has been used successfully over 20 years for simulation, visualization, analysis and improvement of the business-, production- and logistic processes. The basic components library offers a lot of ready to use components for material and information flow simulation but not construction specified objects. Simulation models can build hierarchical to reflect the different levels of operations hence simple elements can be aggregated to modules and modules to complete models.

Due to the fact that all objects inside the simulation model in Plant Simulation are classes, it is possible to extend and derive new sub classes and components which inherit all properties and methods from the parent class, new classes can be instanced later at run-time. These powerful object oriented features and the basics components library make it possible to map the basic process elements in BPMN e.g. Task, Sequenceflow, etc. into the simulation model automatically or semi-automatically even during the run-time or import them all at once to be saved as process templates inside the simulation model.

Table 2 shows some selected simple elements for the mapping between the BPMN process models to the simulation model of Plant Simulation.

Plant Simulation is suitable for material flow simulation where the simulation model objects represent the real physical objects in the factory or the construction site.

The simulation model level is usually one or more-granularity levels below the construction process model level. They show more details and deals with physical objects in the real worlds e.g. machines, materials, transport ways as the example in Table 3 illustrates. Therefore a vertical transformation has to be provided together with the mapping or separately before/after the mapping process.

In Table 4 a few example of possible transformation between process modules (constructs) in BPMN into Plant Simulation are presented.

Table 2. Mapping of simple elements between BPMN to plant simulation.

BPMNProcess element	Plant Simulationelement
Task Activities, Tasks	SingleStation Single station, process
Data Object	Information flow objects: tables, files interface, XML interface, Variables
Sequence Flow	Connector
Timer	SingleStation
Sub-Process	Hierarchy of processes are built using nested Frame objects.
Start Event Intermediate Event End Event	All material and information flow objects have built on events and event listeners.

Table 3. Simulation alternatives using either the physical or abstract level.

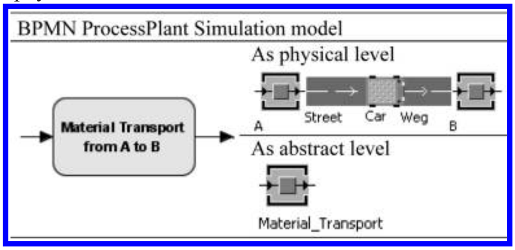
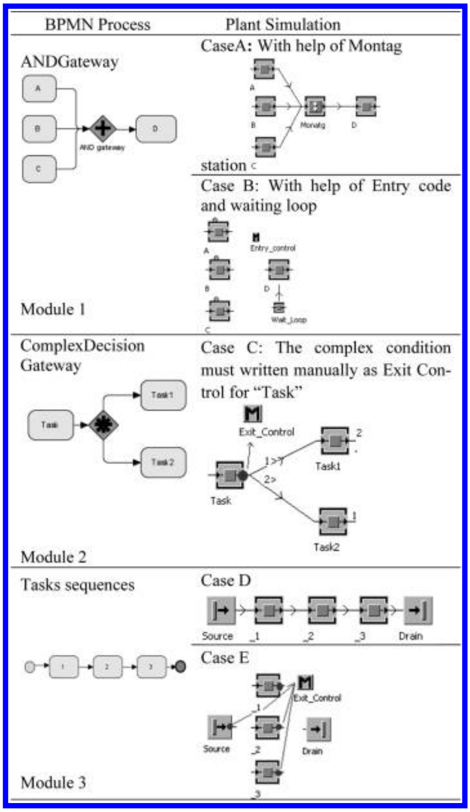


Table 4. Examples of mapping of complex modules from BPMN to plant simulation.



Case A: Merging of tasks A, B, and C in order to produce D. A montage station can be used to ensure that all tasks A, B, and C are completed before task D starts, this kind of transformation is tricky but can be done automatically.

Case B: Merging of tasks A, B, and C in order to produce D but the entry control of task D will check the status of tasks A,B,and C and allow it to start only if all previous tasks have been finished, otherwise a waiting loop will activated, like:

```
If (A.status* B.status *C.status = 1) then
  @.move(D);
Else
  @.move(wait_loop);
End;
```

Case C: The gateway in this BPMN example is a "Complex Decision" for simple conditions the "exit strategy" of the single process "Task" can be used to find the correct way "Task1" or "Task2" for the process according the properties of the product e.g. colour, size, type, etc. For more complex conditions a code must be written and assigned as "Exit control" for the process "Task", in this case an automatic transfer between the process models into simulation models is not possible and a manual modification is necessary after the transformation.

Case D: This is the simplest case for direct transformation of the tasks sequences, the successor task will be fixed through the "arrow" object inside the simulation model.

Case E: in this case the successor task will be determined dynamically through the "Exit strategy" control; this situation can be useful when there is no pre-defined Sequence Flow "Ad-Hoc Processes".

The mapping process for simple BPMN is possible but has some potential difficulties. The process models used in construction engineering often contain no information about the needed time to achieve tasks. This information is important for the simulation model. A user defined properties concerning the duration must be added to the process model objects or gathered after the transformation. A simulation model should always be developedfor a particular set of objectives. This must be clearly defined before the setup of the simulation modelling to formulate the problem and define the system bounds.

Figure 4 shows a transformation for a simple BPMN process "Column erection", the single processes in Plant simulation are extended classes of the standard "Single Station" component, they

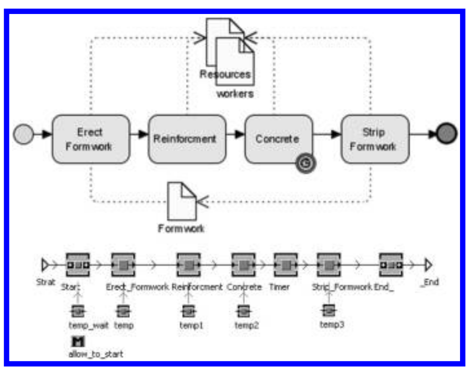


Figure 4. Transformation of Column erection process.

share the same "Resource Pool" and provided with waiting loops to account for resources which are not available in time.

4.3 *Transformation to Petri Nets*

Petri Net (PN) is a well-accepted formalism for modelling concurrent and distributed systems in various application areas: Workflow management, embedded systems, production systems, and traffic control. It provides a uniform environment for modelling, formal analysis, and design of discrete event systems. A PN, which is invented from Carl Adam Petri in 1962, is a graphical and mathematical modelling tool applicable to many systems. PN is both a graphical and mathematical modelling language with a reach theory (such as Reachability Trees, Incidence Matrices, and Invariants Analysis) for analyzing its behavioral (soundness, liveness, reachability, etc.) and structural properties. And it gives a high facility to the designers and managers to model the dynamic features of the system during design and to control the system during operatiohn. Also it provides analytical results with much of the modelling flexibility of simulation.

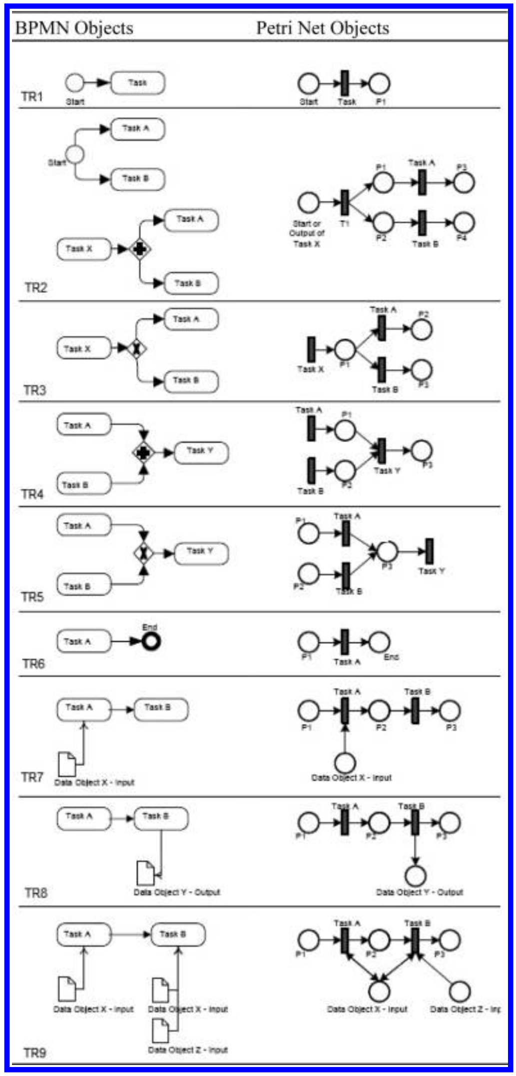
The primary difference between Petri Nets and modellingtools is the presence of tokens which are used tosimulate dynamic, concurrent and asynchronousactivities in a system.

There are two main types in the classification of PNs, which are Low Level PNs (simple nets) and High Level PNs. Low Level PNs are the basic graphical and mathematical representations of models without any extensions. But in the real life systems performance requirements are very important. For that reason several types of PNs (timed, colored, hierarchy, attributed, etc.), which can be used combined each other and separated, were developed.

In project based sectors like building processes, models must be dynamic and ready for the interchange. Interactions between the elements of building process, and (before or during the process) concepts like resource sharing, documentation, cost reductions, etc. are very important. For that reason PN, which is a dynamic modelling language, can be used as verification tool of BPMN or as simulation tool of the model. Transformation of objects from BPMN to PN is given in Table 5. There are three important transformations (TR7, TR8, and TR9) in the Table 5 for resource allocation, organizational units, information sharing, etc.

There is an important point in the last transformation (TR9). The Data Object X may be a resource such as Crane or Digger, which is not consumed after used. In BPMN there may not be any clue about the consumption or reuse of the Resources. But in PN model with only one additional object the user can attach to the resources the information of consumption and reuse. For instance Figure 5 is an instance model, which was modeled first in BPMN (Fig. 2), andtransformed to the PN model. In this example of concrete construction workers, there is a concrete work with resources. However the workflow is the same as in the BPMN model, every common resource is located as only one input place. The simulation of the model can be done with the token game. Tokens are in some places as resources, in others as workflow controllers. The same structure and sequence with the BPMN model is valid alsofor the PNmodel. The tokens were fired until the process stops and the model was verified. In this example

Table 5. Mapping of simple and complex objects from BPMN objects to PN objects.



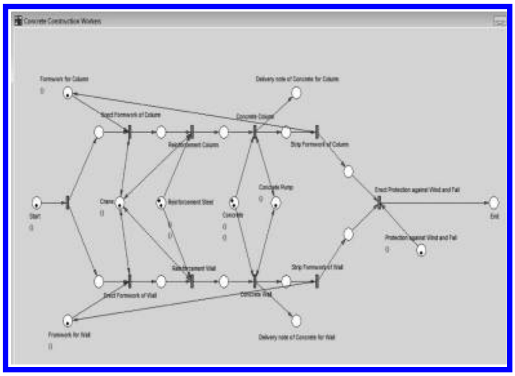


Figure 5. Example of Low Level PN model transformed from BPMN model.

Low Level PN was used to construct the model. Also High Level PNs can be used for more detailed and specialized process models. There are many available PN tools in the Market for this purpose.

5 CONCLUSION

In this paper we presented various methods for automated transformation of process model data to valid simulation model data to support the generation and execution of construction simulations. Whilst such transformations are distinctly different with regard to the applied simulation methods and the underlying simulation tools, they can nevertheless be generalised to adaptable and reusable mapping tasks by:

- Formalizing process data into reusable process modules that can be easily adapted to various specific situations,
- Formalizing simulation model data to correspond to certain repeatable process sequences,
- Harmonizing the use of multi-model resources needed in or controlling the execution of various sub processes (BIM data, construction site and equipment data, cost/scheduling data),
- Developing appropriate mapping patterns for the transformation of various sub processes to simulation model processes and data.

Tables 1–5 showed how this can be done in the case of using AnyLogic, Plant Simulation or, more generally, Petri Net based simulation models. These tables also showed that such mappings are more complex than 1:1 matching of process/simulation objects but that they are nevertheless manageable and can be successfully applied to reduce and make more effective current manual, tedious and error-prone simulation model creation. In this way, much more frequent and higher quality simulation tasks can be included in practical construction planning tasks.

The reported research is an ongoing effort with yet limited scope of results. Detailed findings to the time of this writing are provided in (Marx et. Al. 2010). Planned comprehensive case studies and further development of reference processes and mappings are yet to be done to prove the scope and scalability of the approach and to help refine the suggested transformation methods towards practical exploitation capabilities.

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Service innovation process for the construction industry: Case study of research results transferred to the sector

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ABSTRACT: This article presents the results of a research project aiming at designing innovative collaborative services for the construction sector. On the basis of our case study, we highlight two aspects that we consider important to be closely managed in such science-based innovation processes: 1) the IT/business alignment and 2) the choice of a policy for transferring the results to the sector. These aspects are part of a Sustainable Service Innovation Process (S2IP). In the Luxembourg construction sector the application of S2IP leaded to the design and transfer of collaboration-support services. The alignment issue has been addressed through the elicitation of consensual collaborative practices together with practitioners. Then, after design and development stages, a "mutualist approach" has been chosen to transfer the resulting business services, associating an open-source license of the code to a registered trademark "CRTI-weB ©", identifying the official service delivery in Luxembourg.

1 INTRODUCTION

The Build-IT research project is a project intended for the Construction sector in Luxembourg. During 5 years (2004–2009), researchers and professionals worked together to specify collaborative services adapted for the AEC (i.e. Architecture, Engineering and Construction) activity. The research project focused on two important coordination aspects:

– The building site meeting report management,
– The document exchange.

Based on a specific innovation process (S2IP—Sustainable Service Innovation Process, See section 2), two business services related to these coordination aspects have been developed by implying the end users in the design stage.

This article identifies the specificities of the S2IP innovation process. Then, it presents the application of this process in the AEC sector, and more specifically in the Build-IT research project. The functionalities of the two prototypes resulting from the project are described. The article also states the services transfer approach (i.e. transfer policy, type of license, transfer process). And finally, it identifies some prospects for future projects.

2 SUSTAINABLE SERVICE INNOVATION PROCESS (S2IP)

2.1 *Description of the innovation process*

"Sustainable Service Innovation Process" (S2IP) is an innovation process developed by the Public Research Centre Henri Tudor in order to support innovation in services within open partnerships with the targeted beneficiaries (Chesbrough 2003). This process is based on a participative and collaborative approach of innovation implying the end users in the service design.

This process suggests five principal steps (Kubicki et al. 2009) (see Figure 1):

– "*Service value*" identifies an opportunity for a new service and covers a study of feasibility (i.e. the technological feasibility of the service and the associated business model),
– "*Service design*" focuses on the definition of the service (i.e. functional and non-functional aspects),
– "*Service promotion*" is intended to promote the service after validation by early adopters,
– "*Service management*" is a stage non included in the research center's mission. The service management is attributed to service provider who has to respond to a services contract.

Figure 1. S2IP: Sustainable service innovation process.

– "*Service capitalization*" begins when the service is deployed within organizations. It suggests the collect of user's feedback. This is a source for potential evolutions of the service.

2.2 *Application to the AEC sector*

The innovation process S2IP has been applied in the Build-IT research project (2004–2009). This national project was intended for the AEC sector, and co-funded by CRTI-B[1]. It suggested implying the (future) end users in the design of specific collaborative services. Interviews and working groups allowed identifying the value of prospective services supporting collaboration in construction projects.

This value analysis started before the project with:

– The understanding of the *current state of working practices* in construction projects: how information is managed and exchanged in such projects?
– The *collect of failures' factors* related to the use of Web-based platforms in construction project in Luxembourg. Interviews with practitioners, software vendors helped us in this task, as much as scientific literature state-of-the art (Nitithamyong and Skibniewski 2004; Nitithamyong and Skibniewski 2007).

Then, in the first stages of the project, working groups with practitioners were dedicated to the elicitation of collaborative best practices. The aim was to define repeatable working practices (existing in most of the construction projects), agreed by all the professional trades of building sector in a consensual way.

[1] CRTI-B: Resources center of Technologies and Innovation in Construction. For further information, see: http://www.crtib.lu

Once the practices were identified, we have been able to use it in order to design business services supporting them.

3 SERVICE DESIGN FOR AEC

Our initial aim was to design services supporting collaboration in AEC projects, especially for the building site meeting report management and for the document exchange management. Traditional methods of software engineering often recommend to start with the elicitation of business requirements to be supported by IT and then to implement prototypes.

Literature and professional feedbacks show that it exists a large number of platforms dedicated to project management in AEC, and that most of them remain under-used in a majority of projects cases. Causes have been identified and could be due to IT developments, network capabilities or management of the project's processes supported by IT.

Through our local interviews with practitioners from Luxembourg, we retained essentially that the diverse AEC actor's categories (i.e. architects, engineers, contractors, etc.) have diverging point of views on the use of IT tools in support of the projects. For example, concerning the study about the document exchange, contractors firms, which used to receiving execution plans directly from the architecture agencies, find non-efficient to be obliged to download them from a Web platform. We therefore decided to setup a working group, involving persons representative of the major building trades (i.e. public owners, architects and engineers, contractors, manufacturers…) in order to let them define usual *collaborative practices* in a consensual way.

3.1 *Collaborative practices*

The definition of collaborative practices aims at identifying requirements for future IT services, but at the business level. It was therefore important to identify how people work at high level, without trying to explain micro-processes (i.e. workflows). As construction projects are clearly non-repetitive situations, we wanted to understand high-level practices in order to suggest re-usable services, fitting every situations of project.

Our project has targeted collaboration support. Construction projects are highly collaborative environments involving several actors carrying their own strategy and objectives. Therefore working groups were also aimed at helping practitioners defining consensual collaborative practices, adapted to their own activities.

If for example, we consider the part of the Build-IT research project concerning collaborative practices related to the management of shared documents, in 8 working group sessions, practitioners of Luxembourg defined how the documents were usually shared in projects: documents are named accordingly to a standard name code, versions have to be tracked and managed, modifications on a new version have to be documented, and so on …

A set of collaborative practices related both to meeting report management and to document exchanges has been identified. It has led to two prototypes supporting them.

3.2 *Meeting report management prototype*

The prototype Build-IT "Meeting reports" focuses on the collaborative best practices linked to the building site meeting reports. The prototype is a Web-based application intended to assist the writing and the reading of meeting reports thanks to a standard structure based on composite elements (e.g. references, activity progress, remarks, next meeting, etc.).

This application allows (see Figure 2):

1. Supporting the writing of the meeting reports by notably transferring consistent data from the last report (i.e. opened remarks),
2. Rapidly and efficiently diffusing reports to each concerned person,
3. Accessing at a distance and at any time to building site meeting reports,
4. Dynamically consulting the content of the report and filtering information exclusively dedicated to an organism or another,
5. Searching elements inside reports by keyword and by using diverse combinatorial filters,
6. Commenting a remark that would require more information,
7. Assisting building site meeting by generating a well-spaced text making annotation easier and integrating all comments about the content of the remarks in the report.

3.3 *Document exchange management prototype*

The prototype Build-IT « Document exchange management » allows every stakeholders in a construction project to carry out best practices about document exchange. In the design/construction projects, the diffusion of information is principally based on the documents: plans, descriptions, technical clauses, meeting reports, planning, specifications, etc. Organising the diffusion of information is essential in order that each stakeholder has at his disposal good information at good moment.

Build-IT « Documents » allows (see (Kubicki, Guerriero et al. 2009) for more information):

1. Standardizing the name of the documents according to a convention in order to structure them. It allows efficient search inside a mass of documents, and simplifies upload and download thanks to the Web application,
2. Managing document versions and facilitating traceability of performed modifications,
3. Allowing the assignment of requests between the stakeholders of the project: validation demands, reaction demands, etc,
4. Associating a list of comments to each documents, and supporting direct exchanges between participants (e.g. such as on forums on the Web),
5. Following the most important documents. A notification system allows the user to be informed by email in real time about the activity on the platform,
6. Restricting the document access to certain project members thanks to visibility areas.

These two prototypes, Build-IT "Meeting report" and "Document exchange management" are developed as SaaS (Software as a Service) and rely on open standards (PHP, MySQL, CSS, Webservices).

4 SERVICE TRANSFER

4.1 *Service design output and transfer objectives*

At this stage, the output of our service design project consists in a set of collaborative practices associated with a set of software services, validated through several pilot projects experiments (Kubicki, Guerriero et al. 2009).

In its public mission, CRTI-B aims at promoting innovation and standardization in order to enhance competitiveness of the construction industry in Luxembourg. It was then essential to transfer the services to the sector.

The main aims were:

– To ensure the quality of service delivery, once commercially used in construction projects: availability of service, security of the data, management of the platform users and so on,
– To control the further developments, considered as essential to answer specific requirements or feedbacks from the users,
– To obtain potential royalties for CRTI-B, in order to fund future Research & Development projects enabling the development of new services,
– To keep the property of the "product" and the ability to use it (e.g. in scientific partnerships).

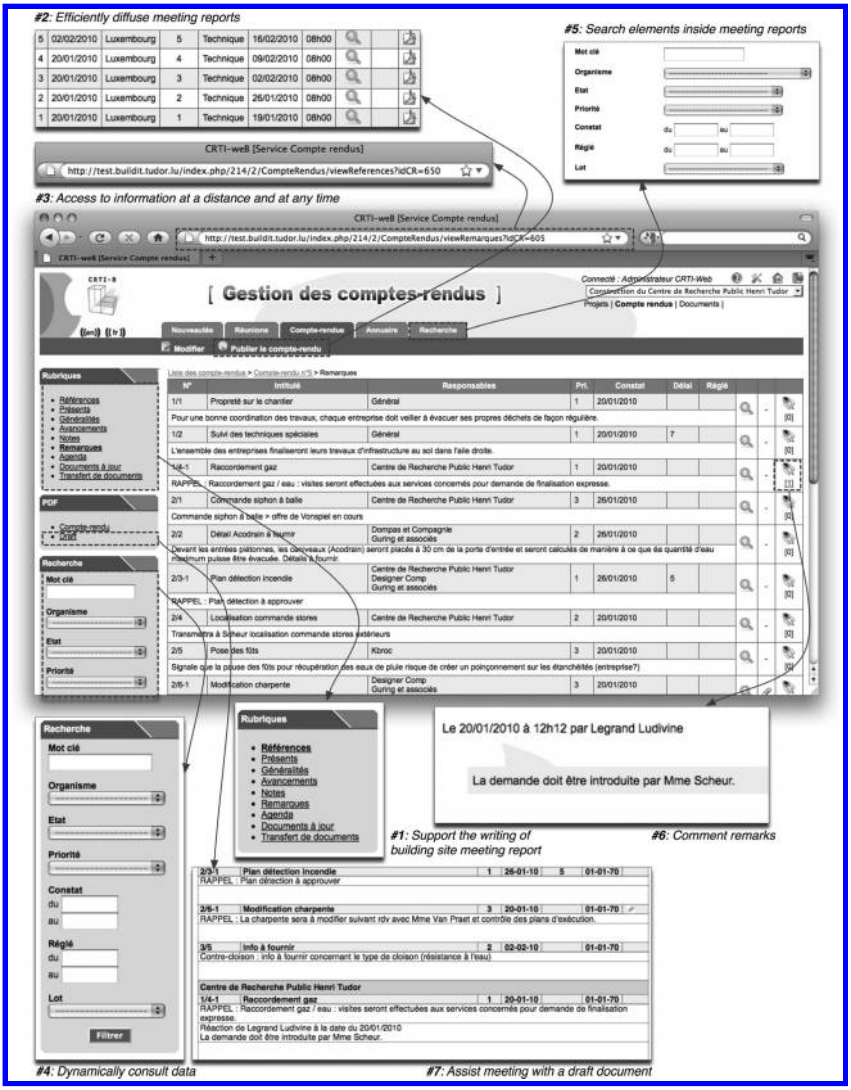

Figure 2. Best practices associated to the meeting report management.

4.2 *Towards a choice of license*

Two approaches were considered for licensing our resulting services (i.e. "Meeting report" and "Documents management" services): the "proprietary licence" and the "mutualist licence".

The "proprietary approach" results from the editors' willingness to maximize the valorisation of their rights of intellectual property linked to the products (Muselli 2004). In this approach the valorisation model is purely economic and the remuneration comes from the concession of licenses to users. The user's rights are limited. Only the editor can access to the source code of the software product and develop new functionalities. Moreover users cannot copy the software product or diffuse it to other persons.

The "mutualist approach" considers that the value is based on a large diffusion of the product more than a large remuneration. In this approach the use of binary code and source code is free of rights (without trademark). In our case, two branches of the product could coexist: one official branch associated to a trademark and a second branch uncontrolled and potentially continuously enriched by a development community. This community can submit the evolutions to the editor and therefore enlarge the functionalities offered in the official branch. In this type of approach the financial valorisation is essentially based on the annexed services and not really on the software product itself.

In the Build-IT project, the CRTI-B has made the choice of a "mutualist model". This model enables diffusing the research project results (e.g. in academic/research collaborations or for private use in architecture/engineering agencies) and the platform of services is available under an open-source license. Moreover the model offers the opportunity for the developed product to really impact the AEC sector in Luxembourg and therefore it contributes to standardization mission of the CRTI-B and to promote the collaborative best practices.

4.3 *Transfer process*

Firstly, a trademark has been registered: "CRTI-weB©". It aims at the identification of the services delivered in Luxembourg under the control of CRTI-B. A set of delivery services is associated to this commercial delivery:

- Management of phone calls: a hotline is available for users,
- Management of issues: methods exist for bugs detection and treatment,
- A FAQ lists most of the issues, and the way to re-solve it,
- Training sessions are proposed to the users, at the beginning of the use of the platform in a project. Then a SLA (Service Level Agreement) is associated to the delivery of these services, and engages the service provider with the CRTI-B.

Once most of the services were defined, we had to find the service provider able to deliver the services. A call for tenders was launched at the end of 2008. An information workshop led us to present the business services (Build-IT platform) and the expected delivery services to regional service provider firms. 4 firms answered the call for tender and one of them was finally retained.

The next stage consisted in finalizing software development, in a close collaboration with our new service provider partner. In the same time, CRTI-B validated the contract with this firm: Service Level Agreement, pricing, royalties, etc.

Finally, the CRTI-weB service is now available in Luxembourg and beyond, since February 1st, 2010. Currently, CRTI-B is being used in the framework of 3 construction projects in Luxembourg (9 architecture/engineering agencies).

5 PROSPECTS

The prospects of this innovation process allow us to distinguish between future innovation services for the AEC sector and open-science issues using the Build-IT research results as basis for other prospective works.

5.1 *Future innovation services*

5.1.1 *Internal client*

The study of the document exchange has highlighted the important link between the two levels of exchange: a collaborative level (specific for the project team) and an internal level (inside an organization). The Build-IT application concerns best practices at the collaborative level. But it is also important to consider internal practices. In collaboration with AEC actors, we have identified internal best practices (e.g. managing documents on a file server, uploading/downloading documents from a project platform, storing modifications lists on document releases, managing internal requests between project team members, etc.) and we are now developing a new prototype exclusively intended for the internal management of documents. This new tool will improve the internal practices and will ensure the interface with the collaborative practices (and Build-IT/CRTI-weB platform).

5.1.2 *Mobile version*

The mobility is an important characteristic of the AEC actors' activity (e.g. presence at the building site, at the agency, etc.). Therefore, we are currently concentrating our effort on a Web mobile version of the Build-IT applications. This new version will allow using the applications on mobile and improving data access. The mobile application will be principally intended to consult information, but will also support light functionalities (e.g. new request on document). In this context, the principal issue and constraint is how to optimize information visualization on a small-screen device.

5.1.3 *Dashboard*

Another prospect consists in defining a dashboard intended for the coordination of the cooperative activity based on data coming from the two Build-IT applications (i.e. meeting report and document exchange). The expected dashboard will consist in a multi-views interface highlighting potential points of dysfunction for the project (e.g. new remarks or comments in the last meeting report, new request on documents, etc.). It will constitute an interesting decision support for the project in the design and the construction phases. Proof of concept prototypes were still designed in previous PhD projects (Guerriero et al. 2010).

5.2 *Open-science issues*

The strong link between open-science and service innovation has been highlighted through this article.

RTOs (Research and Technology Organization) such as the Public Research Centre Henri Tudor now widely recognize that service innovation processes have to be based on scientific inputs. Especially in our case, works in the field of IT enable the setup of a model-driven approach supporting various iterations in service design and IT developments. Then, research works targeting "construction management" allow us to better understand coordination mechanisms existing in building construction activities.

Beyond the Build-IT innovation process and the prospects addressed in our ongoing projects, we aim to define a reverse link through which innovation services designed and transferred could guide a scientific strategy. The basic idea is that once innovative services are designed and begin to be diffused and appropriated by the AEC sector, it is time to en-visage going one step further. We distinguish between two approaches when defining research projects based on the Build-IT transferred services:

– On the one hand, Build-IT services can be considered as "well-documented case studies". Therefore research projects in the field of IT can use it to formulate and validate hypotheses. It is the case of the Dest2Co project aiming at developing a method and toolset for composing services. Future applications of the project results to Build-IT could allow adapting the services platform to particular situations of construction,
– On the other hand, we consider the market penetration of groupware services in the construction sector. Three construction projects are using the CRTI-weB platform at its official launch and we hope this number will increase. Then we can start projects aiming at defining new collaborative practices based on the Build-IT/CRTI-weB innovation step. For example, BIM-based practices could also be identified and a specific version of Build-IT could support them. Two PhD projects are also addressing collaboration issues in the fields of 1) multi-expertise sustainable design of buildings and 2) multi-actors construction simulation. In these projects, one of the goals is to specialize, improve or extend the existing services to prospective requirements, and to validate it in pilot project situations.

6 CONCLUSION

Innovation in construction industry will be an essential challenge for the competitiveness of the sector in the coming years. It is well accepted that IT plays a crucial role, but when designing new services, the alignment between IT and business has to be carefully addressed. Indeed previous research works have shown how IT tools have to fit the users' requirements and to be appropriated by them (Davis 1989; Rezgui, Wilson et al. 2004).

In this article we describe a service innovation process, and try to highlight 1) the importance of aligning IT with business, but also 2) to anticipate the transfer of research results. As a summary, our innovation process especially addresses:

– The elicitation of consensual requirements for services supporting collaboration among AEC partners (i.e. collaborative practices),
– The choice of a policy of intellectual property rights management and the related transfer processes in order to ensure that the innovation will be largely diffused in the construction sector.

A partnership agreement has been signed with a service provider in Luxembourg to deliver the CRTI-weB service to the construction practitioners. The next step in our project will consist in assessing this relationship as well as the quality of the delivery. We also plan to work on the elicitation of new collaborative practices and the design of related business services within a new research project.

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Computer aided education and training

eWork and eBusiness in Architecture, Engineering and Construction – Menzel & Scherer (Eds)

"e-Learning of techniques in Cultural Heritage interventions"

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ABSTRACT: Technology Enhanced Learning (TEL) is an area of increasing interest at working places. Its interest arises from a combination of different factors such as the capability of improving skills and formation of workers, better performance at each workplace, higher flexibility and adaptability contents; distribution, updating and addition of materials with the latest advances; facilities for incorporating implicit knowledge from experts in virtual collaborative environments (including experts in prevention of laboral risks) etc. e-Learning tools require a contextualization of knowledge and an interaction with complex environments with an increasing presence of smart embedded devices. The integration of all these aspects poses very meaningful challenges for modelling, designing and implementing e-Learning strategies. This work is mainly focused towards the design and development of a software application for e-Learning Non-Destructive Techniques (NDT) and Semi-Destructive Technique (SDT) in Cultural Heritage Environments. The developed software application has a modular structure (depending on tasks to be illustrated) following a sequential stratified approach and includes usual common functionalities. We illustrate this software application with image- and range-based 3D documentation (as example of NDT) and a Mechanical Properties (stress, strength, strain) relative to different kinds of Materials which are commonly found in old fabrics.

Keywords: AEC environments, Cultural Heritage Non-Destructive Techniques, e-Learning

1 INTRODUCTION

AEC (Architecture, Engineering and Construction) environments display a very large diversity of scenarios and a very complex dynamics for daily work with a strong need of solving issues under safe and healthy conditions for workers. Very often, a large portion of workers have not enough information or qualification and it is necessary to provide skills on the way to improve performance and, consequently, productivity at working site. This goal involves to a combination of numerical models and behaviors in complex scenarios, where techniques and tasks to be developed must be illustrated in a specific working environment.

Furthermore, conservation and restoration techniques in Cultural Heritage show a very large diversity, and needs an adaptive tool including a range of highly sophisticated techniques with a highly non-trivial instrumentation and a lack of standardization arising not only from the object, but also from experimental techniques. However, the deterioration of large zones of built Cultural Heritage requires a large-scale intervention for historic urban centers or singular buildings.

This work is mainly focused towards the design and development of a software application for e-Learning of Non-Destructive Techniques (NDT) and Semi-Destructive Technique (SDT) in Cultural Heritage Environments [1]. The developed software application has a modular structure (depending on tasks to be illustrated) following a sequential stratified approach and includes usual common functionalities. We illustrate this software application with image- and range-based 3D documentation (as example of NDT) and a Mechanical Properties (stress, strength, strain) relative to different kinds of Materials which are commonly found in old fabrics.

The sequential scheme includes aspects relative to Knowledge acquisition (including self-evaluation), Technological Issues (understanding the application of techniques) and Development of a Collaborative Environment (implicit knowledge from experts and reusing capabilities). The stratified approach for each lesson includes functionalities linked to 1) generation of lesson (methodology for 3D modelling or proofs including remediation of failures), 2) List of questions to be posed in terms of scenarios and advanced instrumentation; 3) Visualization of scenarios related to each question and illustration/evaluation of previous proofs; 4) Elimination, modification or deletion of questions; 5) Evaluation in terms of right answers, 6) Semi-automatic generation of additional lessons from pre-existing ones. In this work some examples relative to 3D documentation and Lab proofs for illustrating methods on different scenarios and with different kinds of materials. Special care is devoted to the visualization module, where a dialogue for learning similar to a video-game has been developed, but with an interactive access to a multimedia database following a reasoning scheme analogous to Second Life paradigm.

Our e-Learning software application has been implemented in Claroline framework. It is a LMS Open Source, a management system for online learning developed under PHP/MySQL which has been developed by the IPM of the Catholic University of Louvain and the ECAM (Higher Industrial Institute) in Belgium.

The adopted methodology of IPM gives autonomy to professor with respect to the chosen pedagogy and the right use of pedagogical techniques for learning. Main motives for the development of software application are linked to the simplicity of use and the independence with respect to the pedagogical disposition. Concerning to pedagogical aspects, it is possible to include documents with posed and solved questions, and the project planning which are based on planning, with a special regard to the collaborative e-Learning.

According to the above general principles, this paper is organized as follows: We start with a very general description of techniques to be learned. Next, we explain the reasons to choose as a tool Claroline software. In the next section we introduce the pedagogical model to be implemented which contains a dynamical representation of learning model. Section 5 is devoted to constructivist approach which seems the most appropriate for acquiring a familiarity with different kinds of techniques. Finally, we show a range of different tools which are considered as appropriate for obtaining a familiarity with the large diversity techniques appearing in the application of Non-Destructive and Semi-Destructive Techniques in Cultural Heritage.

2 TECHNIQUES TO BE LEARNED

Intervention techniques in conservation and rehabilitation tasks display a large complexity due to the diversity of environments, different degree of qualifications by users and tasks to be developed, with a very high degree of variability depending on context. This problem is specially complicated when we consider intervention techniques in Cultural Heritage buildings. Showcases aver very sensitive to interventions, and consequently they provide a benchmark for testing the reaching of different approaches to e-Learning issues.

Intervention techniques on materials to be applied can be grouped in two large categories which are labeled as Non-destructive and Semi-Destructive Techniques (NDT and SDT in the successive). The developed strategy for information management of contents and its advanced visualization related to the e-Learning interventions in AEC environments has been already sketched in J. Burgos et al[1]. Roughly speaking consists of developing an interactive framework where the user can be aware of context, select a technique, identify steps to be done from a well established protocol and evaluate his performance in terms of dialogue situations. The whole dynamic process for e-Learning is illustrated by means of different 3D representations which are connected to a repository of scenes and tasks to be developed, depending on techniques to be used. This methodology is illustrated with the application of a typical Non-Destructive Technique involving to image- and range-based 3D surveying from Photogrammetry and 3D Laser. This illustration is not casual in our methodology, because the visualization of all possible techniques to be applied requires a 3D representation of the scene, for representing the interaction in order to have an intuitive and more friendly interface.

3 THE REASON TO CHOOSE CLAROLINE

The online educational platforms follow the concept of Learning Management System (LMS)

To consider a quality LMS different aspects are considered among the most important are:

International presence (how many institutions are using it and its successful experience)

Didactic flexibility, which is useful for the diversity of modalities (face course, blended learning course / or virtual course) and teaching styles and learning content that can be used in various formats, with different purposes and levels of complexity, both for training students, researchers and administrative staff.

[1] J. Burgos, A. Hurtado and J. Finat: Towards a TEL-platform for improving trust and security in construction environments, ICERI, Madrid 2009.

Usability, ease of use must be simple, intuitive, comfortable and friendly, anyone with basic knowledge of conventional software, with appropriate training can browse and ownership of the technology without investing large amounts of machine hours.

Technological flexibility; that is scalable, allowing the development, set and reset the software to institutional needs; that is accessible from any remote location that can access learning resources; that is adaptable to be able to customize teaching to the needs of students; to be profitable, that can increase production and efficiency with low costs and short time; that is interoperable, which can use the learning resources that were developed in other LMS and other LMS can use the resources developed in the own (export SCORM courses).

The importance of this approach is crucial for cost savings for educational institutions and content production companies: if learning objects are designed and built correctly and also conveniently categorized and archived, can be easily utilized in multiple contexts and better monetizing the high investment needed for their development. This advantage is accompanied by a no less important: the creation of so-called learning object repositories, clearing houses authentic educational materials that likely will become one of the pillars of e-learning in the near future.

The aim is to develop knowledge, skills, attitudes and values, and not only the instrumental use of a computer program.

3.1 *Aspects relevant to the choice of Claroline*

- Provides the necessary tools that were intended to have an application referred to the Rehabilitation Task Learning in AEC environments [Architecture, Engineering, Construction] Multimedia on different supports [Text, Image, Video] referenced 3D scenes.
- It is an open source application.
- User-friendly interface, simple, attractive and intuitive.
- A large community of institutions used worldwide Claroline [2].
- The methodology of Claroline (5 pillars) is set to the most appropriate methodology for learning the techniques of intervention.
- Meets the three aspects of a quality LMS: didactic flexibility, usability, technological flexibility.
- Enables import and export content in SCORM format.
- Multilanguage application. Allows users to select their language from more than 35 different (not all are translated to 100%). Allows easy adaptation to any language.

Figure 1. Adaptation of Claroline for the developed ATRAECoM software application.

- You can easily add and remove modules, tools, change the interface.
- In the multimedia environment offers improved functionality and interactivity. It has more interactive chats and video conferencing tools.
- Enables the construction of learning paths. They are learning sequences that must be followed to be accessing different resources. It is useful to allow access depending on the level of knowledge that the user to prove in a previous questionnaire.
- It has group management tool.
- Advertising tool available.

4 PEDAGOGICAL MODEL

An important aim of e-Learning Tools is the learning promotion from the organization of well planned strategies focused towards the consecution of main goals. For Claroline-based applications, main components or pillars for acquiring knowledge are Information, Motivation, Activities, Interaction and Contents production.

Pedagogical model of Claroline [3] [4] can be used for promote, design and evaluation of innovative aspects inside a firm or an institution. In this way, the implicit or explicit know-how can be transferred in an interactive way. In e-Learning tools the most important component is not the "e" of Electronic, but the learning process by itself, or in our case, their translation to training in conditions as similar as possible to the real work environments.

In the next figure, one can see a dynamic representation of a Claroline learning model, with the above cited 5 pillars which can be used for designing a large amount of devices which promote Learning and Training following a complex dynamics in AEC environment. Nowadays our approach concerns mainly to interaction with environment, not with other workers.

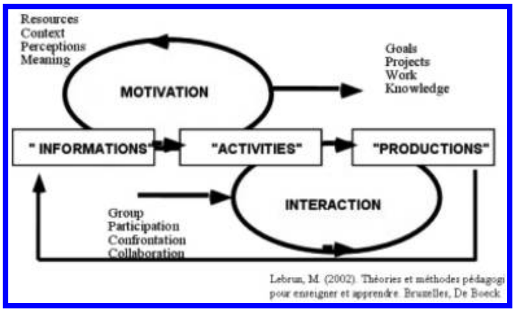

Figure 2. Dynamic representation of our learning model.

Three rectangles appearing in the below Figure 2 are inspired by the constructivist approach (see section 4 for details).

Motivation and Interaction provide two feedback "loops" for representing the transformation of information in knowledge from learner activities; the knowledge generated in this way provides a feedback (systemic loop). This process is allowed by motivation factors and empowered by the different kinds of interaction with the environment (functional interaction) or other agents (shared interaction) given by other students or learners.

4.1 *Motivation*

Contextual aspects have a great importance and they are provided by a simplified but realistic representation of environment. The development of specific tools for workers arises from a reelaboration of materials provided by firms, which include some aspects which belong to the specific know-how of firms. The provided information allows to be conscious of the performed work, standing achievements and work to be done. In this way, it is possible to determine the performance of acquired knowledge.

4.2 *Interaction*

It is a collaboration task between learner and teacher. It is necessary to design a specific policy for supporting and encouraging activities along the learning process. This process involves to the design of activities regarding the environment and other students, according to the above approach.

5 CONSTRUCTIVISM

The constructivist approach intends to give an answer to "why?" which corresponds to high level thinking which promotes the personal acquisition of a meaning and a contextualized learning. Following the constructivist psychology, students interpret the information and even the World according to their personal reality.

In this case, learning is produced by a combination of observation, processing, interpretation and individualization of information in personal knowledge (Cooper, 1993[2]; Wilson, 1997[3]). Learning achieves better results for students when they are able of locating the contents in its context for the most immediate application and by the personal meaning which they are able of associating by means of some kind of attribution process.

Following an increasingly used terminology, the constructivist approach is focused towards the subject (user centric), instead of acquiring knowledge along the instruction. This knowledge construction must be contextualized (Hung, Looi and Koh, 2004[4]) along the on-line learning process. Because of this, it is very important the design of some kind of storyboard for representing and visualizing different stages for the task to be developed.

6 SOFTWARE TOOLS

Claroline is a software tool having different Tools for developing components or pillars which are used for promoting learning process. In the next figure, we display the learning model with different sub modules and corresponding tools which play the role of catalyzers.

Along the Table 1, we display a recopilation of different tools with different factors for promoting learning in terms of methodological pillars which follow the developed application. This approach is compatible with NDT and SDT in trying of solving Accessibility issues or conservation and restoration tasks.

6.1 *Tools and some of its possible applications*

- *Calendar.* The professional can use the calendar as a personal organizer where you can pick events with several actions have to perform

[2] Cooper, P.A. (1993). Paradigm shifts in designing instruction: From behaviorism to cognitivism to constructivism. Educational Technology, 33(5), 12–19.
[3] Wilson, B.G. (1997). Reflections on constructivism and instructional design. In C.R. Dills & A.J. Romiszowski (Eds.), Instructional development paradigms (pp. 63–80). Englewood Cliffs, NJ: Educational Technology Publications.
[4] Hung, D., Looi, C.K. & Koh, T.S. (2004). Situated cognition and communities of practice: First-person 'lived experiences' vs. third-person perspectives. Educational Technology & Society, 7(4), 193–200.

and congress events, conferences, lectures, etc. consider interesting for their work.

- *Classifieds*. Section where you can include news, articles, videos and all kinds of documents that help to improve the learning of different techniques.
- *Documents*. Allows you to share with other professionals who use the application all file types associated with techniques in cultural heritage interventions.
- *Learning path*. Allowing the monitoring of a range of activities, exercises, tests, etc. to acquire knowledge about the various techniques. The learning paths have different levels of difficulty for professionals with previous knowledge to go directly to the desired level by undertaking a test of the previous level.
- *Jobs*. Professionals can make theoretical and practical work through the application that will be corrected by experts in the various techniques as a way to supplement learning.
- *Forums*. This tool can be used as a forum to exchange views on issues of concern to users of the application and as a means of dissemination of new techniques and updating existing ones.
- *Users and Groups*. With these tools can be managed individually the different professionals and creating professional groups in order to facilitate the administration and operation of the course on intervention techniques.

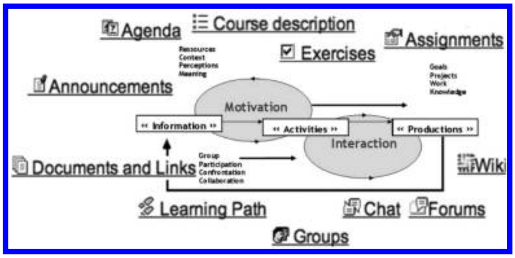

Figure 3. Claroline learning model and SW tools.

Table 1. Claroline pillars and tools.

Pillar of learning methodology	Factors for promoting learning	Appropriate tools
Information	*Transmission* of contents (only the first step) *Inform* about possible choices, pedagogic availability	Links and documents
	To give learning goals and evaluation criteria	
	Illustrating the context *Show* the path going from knowledge and previous qualities till the new ones	Announcements
	Provide tools for evaluating new knowledge (proofs, evaluation sheets) instead of traditional exams	Calendar
	Provide sources/ resources with small difficulties for encouraging learning process	Main page of the course
	Provide well chosen *web links*	
Motivation	*Underline* previous knowledge and already present capabilities.	Description of course
	Make more clear general and specific objectives	Links and documents
	Illustrate and underline the important of new knowledge and qualities for learning procedure.	
	Show the context for the use of new knowledge	Announcements
	Accurate exposition of instructions and agenda *Make comments* about task interest and its value.	Calendar
	Some crucial issues are the following ones: Which are the degrees of freedom and controllable part of activities?	Learning path
	Which are the interaction or feedback elements?	Main page

(*Continued*)

Table 1. (*Continued*)

Activities	*Give* a temporal scenario by showing different steps or stages *Propose* Tools for working with the information (analysis tables, exercises)	Course description
	Consider additional activities away the platform (it is advisable to use available libraries and/or Internet *Impulse innovation,* by diversifying and living coherent activities	Exercises
	Develop tools (exercises, primarily) for evaluating new acquired knowledge	Learning path
	Foment of the alternance between lectures, exercises, problems, cases, applications**.** *Develop* activities for demonstration or reuse of some simple task	Practices
	Alternate individual (convergent) and collective (divergent) work for cooperation in teams	Blogs
Interaction	*Choose* appropriate tasks (it is necessary to develop a work by means of a group)	Users
	Perform a group of *instruction* and modelling activities for promote the interdependence	Blogs
	Promote the apparition of multiple viewpoints	Groups
	Give the opportunity of exerting a critical mind	
	Realize observations to students	Chat
	Give time for a personal reflection	Wiki
	Find an "intermediate point between flexible and rigid behaviour, between thought and divergent synthesis"	
	To exploit the utilities of written discourse (in blogs)	Calendar
	Proper Use of advantages of synchrony and asynchrony tools	Announcements
Productions	*Realization and recognition* of new knowledge	"Home works"
	To give the opportunity of realizing a goal a writing, a signal, … which can represent a new knowledge *Provide* time for publishing, communicating and exchange of conclusions	Exercises
	Design of activities for evaluating goals with evaluable criteria.	Blogs
	Design of activities for dilucidate the acquired and Licking knowledge, including skills or abilities for the realisation of specific tasks	
	Call the attention about new problems and challenges.	Documents
	To try of interesting to students to become consorcious of their new learning and knowledge	Learning path

- *Chat and video conferencing*. Allows real-time communication between professionals to discuss different aspects of their performances, answer questions and to take joint decisions that lead to a better application of intervention techniques.
- *Media center*. Tool that provides a container for all types of multimedia elements that can be found among the videos on the protocols for working in a job rehabilitation, conservation, etc., explanatory audios, podcasts, and maps from Google Maps with the location of the areas for action.
- *Editor of the application*. The editor that provides the application allows you to insert images and mapping, incorporating interactivity in the picture, access to other resources, etc. You can also insert their own videos in different formats or from repositories of streaming video.
- *3D object viewer.* Tool that lets you view 3D files in standard formats.
- *Editing and retouching of images*. Allows editing images, retouching, applying filters, etc.
- *Video editing*. Allows you to edit video, add frames and links.

7 TWO CASES OF USE

For illustrating the above general scheme we have developed the Claroline methodology to two cases of use involving a typical NDT which is linked to image- and range-based documentation of 3D objects, and on the other hand to evaluation of efforts in typical materials which one can found at classical fabrics linked to variable loads whose mechanical properties are controlled at specific Labs.

First one takes in account a lot of work performed by several experts of the University of Valladolid (Spain), whereas the second has been performed in R&D department of the firm Geocisa (Madrid) in regard to some essays previous to interventions in Cultural Heritage environments.

8 CONCLUSIONS

Conservation and restoration tasks are work intensive and require an increasingly qualification which, very often, must be provided in situ. In this work, we have adopted the Claroline methodology for developing learning principles linked to NDT and SDT applied to interventions in Cultural Heritage environments. Specific troubles of the proposed methodology are illustrated with three-dimensional surveying of buildings and mechanical properties of materials appearing in traditional fabrics in Cultural Heritage buildings.

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Master programme in IT in Architecture, Engineering and Construction—Lessons learned

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ABSTRACT: This paper describes the structure of and experiences gained from delivering the MEngSc Program entitled "Information Technology in Architecture, Engineering, and Construction". The program was developed using the achievements of the ITC-Euromaster Project—an EU-Tempus/Socrates project funded by the EC from 2001 to 2005 and led by the University of Maribor. Based on this material University College Cork has developed a fully accredited MEngSc program commencing in the Academic Year 2006/2007. The programme is offered for both full-time and part-time students. Lectures and seminars are delivered in the first two terms of the Academic Year, including two project-centered modules in the second term. After successful completion of all exams students can progress with their Master Thesis in the third teaching period (June to September).

The second part of the paper shares with the reader experiences gained since 2006. We report about the technology used and its reliability, the material prepared and how it is shared and used by the students, and last but not least the feedback from students and their "success stories" after graduation.

1 A POSTGRADUATE COURSE POOL

Undergraduate courses and graduate programs in the area of IT in AEC are offered in Germany, Sweden, Denmark, The Netherlands, Switzerland, Austria, the USA, Canada, Australia and New Zealand. Turk and Delic (2003) developed a proposed core undergraduate curriculum for the Bologna undergraduate model. At the graduate level, team oriented, project-based scenarios are used in several distant education courses in AEC. The best known course is Stanford University's P5BL Course, which has been running for more than a decade now (Fruchter 1996). Most of these courses force students to use information and communication technology in order to learn the underlying principles of IT in AEC (Menzel 1997, Bento et al. 2004). The maturity of these topics has been proven by some excellent books with engineering examples and exercises (Raphael and Smith 2003).

IT in AEC is still a new topic which is rapidly developing. In research, critical mass was achieved by creating international, collaborative research projects. To spread the research results through teaching, the same kind of critical mass had to be achieved. Forces have been joined to develop an international, multi-institutional postgraduate program (ITC Euromaster 2005). In 2001seven European universities started to develop a new postgraduate program in IT in AEC. The program development was funded by the European Commission through the Socrates/Erasmus framework between 2001 and 2005. Two more partners joined in the program dissemination process.

The main purpose of the ITC-Euromaster project was to develop a commonly agreed upon curriculum in IT in AEC. This curriculum should complement the existing portfolio of teaching programs and should meet the growing demand for IT-skills in the AEC-sector. The development of the individual modules in the curriculum was coordinated by a responsible partner institution. Teaching materials have been prepared in digital form, conforming to available e-learning standards.

Based on the results of a skill audit, the review of existing courses at partner institutions, as well as market research and analysis, a course structure has been developed consisting of 12 subjects (Table 1). The curriculum is focused on students who have finished their undergraduate studies with a university degree in civil, building or structural engineering as well as architecture. The program graduates earn a "Masters in Information Technology in Architecture, Engineering, and Construction" academic degree, which shall enable them to continue with the relevant PhD study or immediately start to work in the industry as civil engineers with a specific focus on Information Technology.

Table 1. Modules offered in the programme.

#	Title	Comment
First term		
1a	Software Engineering	5 cr (C)
2	Computer Aided Facilities Mgmt.	5 cr (C)
3	Computer Mediated Communication	5 cr (C)
4a	IT for Energy in Buildings	(**)
5	Engineering Artificial Intelligence	5 cr (E)
6	Virtual Enterprises	5 cr (E)
	Mobile Systems Design 1(CS)	(*) 2009
Second term		
1b	Software Engineering (Project)	5 cr (C)
4b	IT for Energy in Buildings (Project)	10 cr (C)
7	eBusiness in AEC	5 cr (C)
8	Mobile Computing in AEC	5 cr (C)
9	Virtual Construction	5 cr (E)
10	Information Modelling & Retrieval	5 cr (E)
11	Finite Element Methods	5 cr (E)
	Mobile Systems Design 2 (CS)	(*) 2009
Third term		
12	Thesis	30 cr (C)
Previous subjects		
	Knowledge Management	(*) 2008
	Artificial Intelligence (CS)	(*) 2008

LEGEND:
(**) 2 terms, credits awarded after project
(*) {*Year*} withdrawn from curriculum in {Year}
(C) compulsory
(E) elective

1.1 *Course objectives at university college cork*

UCC introduced the Master Programme for Information Technology in Architecture, Engineering, and Construction as a response to the increased need for qualified IT specialists who are able to use and develop the new information and communication technologies in Architecture, Engineering, Construction (AEC) and Facilities Management (FM). Participants obtain a knowledge and hands-on experience in planning, designing, and maintaining state-of-the-art information and communication technologies for the needs of the AEC & FM-sector with an emphasis on Smart Buildings.

The programme is designed for AEC-practitioners as well as young graduates of all AEC-related engineering disciplines, who wish to improve their IT-knowledge. Vice-versa computer scientists can improve their knowledge about one major application area for complex IT-systems.

1.2 *Course content*

The subjects are divided into core compulsory subjects that have to be taken and elective subjects from which students have a choice. During the Introduction Week at the beginning of the first term students are introduced to course modules and academic staff. Participants get in contact with each other, develop their own contacts within the group and "set-up" their ICT-equipment.

The core subjects that have to be taken in the first term are Software Engineering –Part 1 -, Computer Aided Facilities Management, Computer Mediated Communication and Energy Systems in Buildings. Students can accumulate a total of 20 ECTS-credits. The Electives in the first term are Virtual Enterprises, Engineering Artificial Intelligence, and Mobile Systems Design. Two electives have to be chosen in order to compile another 10 ECTS-credits.

The second term consists of Software Engineering—Part 2 -, IT for e-Business in AEC, Mobile Computing in AEC, and Energy Systems in Buildings—Part 2 -. Again the number of the credits for the compulsory subjects amounts to 20 ECTS-credits. The Electives during the second term are Virtual Construction, Finite Element Analysis, Information Modelling and Retrieval and Mobile Systems Design 2 in AEC. Two electives are required to give an additional 10 ECTS-credits.

In the third term, after completing projects and exams, students work on their Minor Research Thesis. The programme supports research lead teaching and therefore, participants are encouraged to select their topic from research areas closely linked to their areas of expertise. Additionally, students are strongly encouraged to consult current or potential employers/industry partners to define their topic in the area of Industry-Lead Research.

Table 1 below summarizes the course structure and gives a consolidated overview about the modules delivered.

1.3 *Targeted audience and delivery mode*

The course is designed to cater for fulltime and part-time students. Fulltime students complete the course in 1 year whereas part-time students can complete over a two year period. Fulltime students are required to complete a taught 30 credits in term 1 and 30 credits in term 2. A further 30 credits are given for the completion of a minor thesis. Those opting not to take the thesis are awarded a Diploma after successful completion of their Exams in Spring.

Part-time students must also complete a minimum of 30 credits in the first year although they may if they want increase the number of credits which means having fewer subjects to cover in the second year and thus more flexibility to tailor their project modules to the needs of their current or future employer.

At least two modules per term are delivered on a Weekly Format, i.e. Lectures and Seminars are delivered after 17:30 on one day of the week over all 12 weeks of the term. These subjects are usually lectured by the Course Coordinator to ensure a continuous weekly contact with all students.

As one can see in Table 2 most subjects are delivered in "Block –Format". In this case four lectures are delivered at one evening from 17:30 to 19:00 over for weeks. These lectures can be attended from either remote locations or on UCC campus. The majority of the lectures will then be delivered in one "Week-End-Block" on Friday afternoon and the whole Saturday. This gives Part-Time Students and Guest Lecturers an option to travel to Cork and to attend/lecture on UCC campus. However, there is no obligation to attend or deliver lectures in Cork, since in all phases of the programme Collaboration tools are provided and are accessible.

The delivery mode described in the previous paragraphs has multiple advantages:

- Part Time students can attend lectures (from remote locations) after work hours,
- Full Time students can intensively work on assignments and projects and can liaise with tutors, since they are provided with dedicated Lab-facilities.

Table 2 below gives an overview about the explained delivery modes at a glance.

1.4 *Grading and examination*

We distinguish into modules focusing primarily on knowledge acquisition, nodules focusing on knowledge transfer and modules focusing on project Based Learning.

Modules focusing primarily on Knowledge Acquisition are usually delivered in a split of 24 lectures (each 45 min.) and 10 to 12 seminars (each 45 min.). These modules are examined with written exams. Students have to work on small assignments graded as so called Continuous Assessment (CA). Exam results are weighted with 60%, CA with 40%.

Table 3 below gives an overview about modules focusing on Knowledge Acquisition.

Modules focusing primarily on Knowledge Transfer are also delivered in a split of 24 lectures (each 45 min.) and complemented by 10 to 12 tutorials (each 45 min.). However, these modules are examined 100% as CA. Student work either on an essay or they work on a complex assignment and tutors guide them through the complex task. These modules are tailored to prepare students for the project-oriented modules. Table 4 shows the relevant modules.

The modules Software Engineering—Part 2—and IT for Energy Systems in Buildings—Part 2—are carried out by means of a project during which students work on a R&D-relevant topic. Students must give at least two intermediate presentations on the progress of their projects culminating in a final presentation. Presentations are complemented by a comprehensive project report.

Table 2. Mode of delivery.

Week	Block Format (4 weeks plus 1 week end)	Weekly Format
First term		
01	Module 3, 1a, 3 and Intro	Module 2
02–04	Module 3	Module 6
05–08	Module 5	
09–12	Module 4a	
Second term		
13–16	Module 8	Module 7
17–20	Module 9	Module 11
21–24	Module 10	Module 1b Module 4b
Third term		
25 to 36	Module 12	

Table 3. Subjects focusing on Knowledge Acquisition.

#	Title	Comment
Knowledge Acquisition		
1a	Software Engineering	Autumn
2	Computer Aided Facilities Mgmt.	Autumn
7	eBusiness in AEC	Spring
8	Mobile Computing in AEC	Spring
10	Information Modelling & Retrieval	Spring
11	Finite Element Methods	Spring

Table 4. Modules focusing on Knowledge Transfer.

#	Title	Comment
Knowledge Transfer (CA only)		
3	Computer Mediated Communication	Autumn
4a	IT for Energy in Buildings	Autumn
5	Engineering Artificial Intelligence	Autumn
6	Virtual Enterprises	Autumn
9	Virtual Construction	Spring

Table 5. Project-oriented modules.

#	Title	Comment
Project Based Learning		
1b	Software Engineering (Project)	Spring
4b	IT for Energy in Buildings (Project)	Spring

2 INFRASTRUCTURE

The available infrastructure at UCC consists of one fully equipped Laboratory for Remote Learning (SceneLab 2), a Seminar Room two PC Labs equipped with AV-technology and data projector, the Collaboration Platform (currently AdobeConnectPro), and the ITC-Course Portal, jointly used with the University of Maribor. We will explain the components in the next sections.

2.1 *SceneLab 2*

SceneLab 2 is the "home base" for the MEngSc-Programme on IT in AEC at UCC. It provides up to 32 seats and is a multi-functional laboratory equipped with state-of-the-art collaboration technology, such as a Smart Board, a Data Projector, Boundary Microphones, an Audio System, Dimmable Lights, and last but not least a wireless Central Media Control Unit.

2.2 *Laboratories*

UCC has equipped two PC-Laboratories with AV-equipment in order to facilitate the delivery of seminars and tutorials from remote locations. Additionally UCC operates a Post Graduate IT-Lab that is especially equipped to facilitate the set-up of meetings with mentors and lecturers from remote locations.

2.3 *Collaboration technology*

Lectures are broadcast using web technology and can be attended either from UCC, at home or in ones workplace. Students, who wish to participate in Lectures and Seminars from remote locations, need the following ICT-infrastructure at home or in their office—Notebook or PC, USB-Camera, Head-Set, Broadband Access.

Figure 1. Lecturing theatre SCENE-LAB 2.

Based on our experience the number of students who prefer to use their own laptop increases. Table 6 below gives an overview about the IT-equipment used by students and the percentage of students using their own laptop.

The Collaboration Platform consists of a multi-point broadcasting unit, allowing participation in lectures and seminars from remote locations, and desktop client software. The Collaboration Platform is used to share audio and video during lectures and also share presentations and applications during lectures, seminars and tutorials. Table 7 gives an overview about the total number of modules with remote components.

The Portal is used to share general information, such as timetables, contact information, share lecture material, provide an exchange platform,

Table 6. Students' IT equipment and % of remote participation.

Academic Year	# students enrolled	# remote students	% of students with own Laptop
2006/07	(3+2*)	2	40%
2007/08	5	2.5	40%
2008/09	13	2	30%
2009/10	19	4	40%

Figure 2. Example for "Student-Kit".

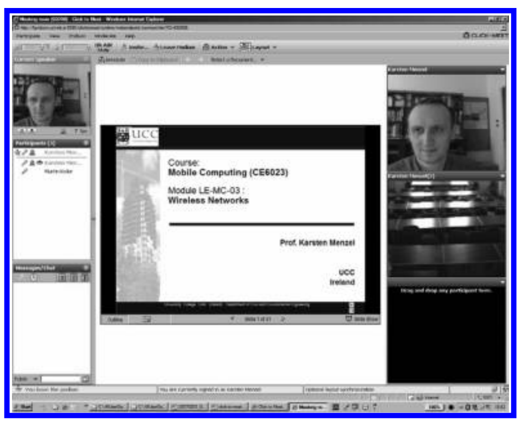

Figure 3. Screenshot collaboration platform (1st Generation).

Table 7. Number of modules with remote components.

Academic Year	Modules taught from remote locations	% of remote teaching per module
2006/07	8 modules	approx. 30%
2007/08	8 modules	approx. 30%
2008/09	6 modules	approx. 40%
2009/10	3 modules	approx. 60%

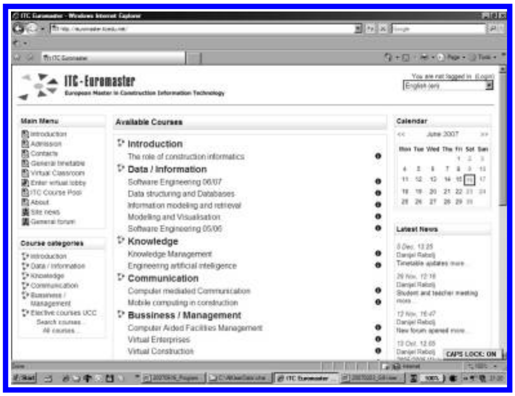

Figure 4. Screenshot course PortaIn.

Table 8. Intensity of usage of dedicated Portal-Features.

Academic Year	Down load	Calendar	News Group	Other
2006/07	37%	0%	0%	0%
2007/08	55%	20%	20%	0%
2008/09	75%	55%	20%	0%
2009/10	86%	75%	40%	7%

including teacher's and student's forums. The Portal is operated and provided by the University of Maribor. The content is managed and maintained by the individual lecturers.

Table 8 below gives an overview what features of the Portal have been used over the past four Academic Years. One can clearly see that the major purpose of the Portal in the early years of the programme was focusing on the distribution of lecturing material.

In the later years, and with growing student numbers more advanced and team management features have been used by lecturers and students.

Additionally, the Chair for Information Technology in Architecture, Engineering and Construction operates multiple prototypical RFID-based demonstrators in SceneLab 2, such as a UHF-gate reader and a decentralised maintenance information management platform.

3 STUDENT'S PROFILE

When the course started in 2006, the first cohort consisted of three students plus an additional two ERASMUS students. Out of the three UCC-students were one an undergraduate and two returning as students having gained industry experience. One was a graduate in Computer Science whilst the other two where a mechanical engineer and a project manager. All three undertook fulltime study.

The second cohort consisted of fulltime one civil engineering graduate and 4 industry experienced part-time students who were in three cases structural engineers whilst the fourth was from a project management background. One of the part-time graduates eventually left employment and returned to academia to study for a PhD.

The third cohort rose to 11 students. Of these there were 2 part-time students and 9 fulltime students. The mix of graduates to those from industry was evenly divided and proved invaluable as those with little industry experience were able to gain from those who had experience.

The fourth and current cohort numbers 17 and again the mix of graduates to those from industry are evenly divided. The number of experienced students returning to college may however have been influenced by the current economic climate as many see undertaking such a qualification as a means to provide more security in retaining ones position within industry. It is also true that graduates with few job opportunities' see undertaking a higher level as giving them the edge so to speak.

Form experience to date the mixture of graduate and those with experience has been of great value to the group as a whole.

The programme allows for a student intake from multiple disciplines in order to reflect the interdisciplinary nature of the construction sector. Table 9 below gives an overview about the various professional backgrounds of the students who have been enrolled in the programme since 2006.

4 PROJECT BASED, RESEARCH LED TEACHING AND LEARNING

4.1 *Team oriented work*

Modern Information and Communication Technologies, such as video conferencing, application sharing, knowledge sharing or messaging, are becoming a 'natural' part of our work environment and embedded in most of the business processes in the AEC-sector.

Therefore, we strongly believe that the development of soft skills, such as teamwork and

Table 9. Professional background of graduates.

Academic Year	Architecture	Engineering (Civil)	Engineering (other)	Construction Management	Computer Science
2006/2007		1	1	1	2
2007/2008		4		1	
2008/2009		8	3		
2009/2010	2	4	8	2	1

presentation skills, is essential for the success of our programme. Through the set-up of assignments and projects team-oriented work is stimulated in all phases of the curriculum.

For most of the assignments an "Umbrella Topic" is defined. This "Umbrella Topic" delivers a "real-world" context for assignments, homework, etc. Students are challenged to consider and analyse problems from a broader perspective.

In modules focusing on Knowledge Transfer (see Table 4) a group of 2...4 students must join forces to develop a holistic, consistent solution to a problem described in the "Umbrella Topic". Nevertheless, each assignment delivers a unique contribution to the overall solution and can be graded on an individual basis.

4.2 *Projects*

Two projects are running in parallel and are usually thematically connected with each other. The project module in Software Engineering emphasizes on IT aspects and is complemented by the module IT for Energy in Buildings which emphasizes on the devel-opment of an engineered solution requiring strong ICT-support. However, a combination of the Soft-ware Engineering project with other modules such as FEM, or eBusiness is possible.

It is the didactic objective of the project modules to prepare the students for their work on the Master Thesis.

4.3 *Master thesis*

Potential topics and challenges for the Master Thesis are based on the research of the Chair of "Information Technology in AEC" or problems identified in the work environment of current or future employers of the students.

Currently, our research focuses on the following areas:

Wireless Sensors, RFID-Technology and Mobile Computing, to support efficient process and supply chain management as well as sustainable, energy-efficient management and operation of built artefacts.

Energy and Facilities Management using multi-dimensional Information Systems to enable holistic, consistent, and context-oriented information management and performance analysis of complex engineering systems.

Business-Process Modelling and Collaborative Work: to enable cross-sector co-operation and new business patterns, such as PPP (Private-Public-Partnerships), ESCO (Energy Service Companies), or CN (Collaborative Networks).

Research in this area focuses on integrated data and information management of buildings and related management processes from 'cradle to grave'.

Multi-dimensional information systems allow for accessing, analysing, and maintaining complex information spaces in a context-sensitive way. Decision support is supported for different use cases and stakeholder profiles.

Cloud computing supports the integrated management of locally distributed but homogeneously classified data and information as required in the AEC-sector.

The major objective of the Master Thesis is the independent development of a unique scientific solution to a given problem. Given the twelve weeks timeframe the problem to be solved must have a limited scope and the development of the solution must be focused. However, through the sequential combination of project modules with the Thesis the students are well prepared to address these challenges.

Figure 5. Teamwork and remote collaboration with ICT.

4.4 *Joint work with other Post Graduate students*

In all phases of the curriculum PhD-students and Post Doctoral researchers act as tutors and mentors to the Master Students enrolled in the programme. The benefit for the group is twofold. Researchers in their early career stages benefit from the practical experience of students who already worked in industry and vice-versa students with an industry background benefit from the in-depth ICT—expertise of the young researchers.

5 INTERNATIONAL EXCHANGE

Our programme is embedded in a strong European and International community; namely the collaboration with the 'Global Teamwork Experience' Programme at Stanford University in the USA and the ERASMUS programme of the European Union.

5.1 *Global Teamwork Experience (GTE)*

Commencing in the Academic Year 2008/2009 UCC has delegated the top student to Stanford University to participate in the 'Global Teamwork Experience' Programme. The Stanford programme focuses on the development of design skills through project-centered learning.

Each year a team of 30 to 40 students from different countries, such as Germany, Sweden, Slovenia, Ireland, Hawai, and multiple States of the USA and with different qualification profiles, such as Architecture, Structural Engineering, Mechanical Engineering, or Construction Management is selected by Stanford University to work collectively on the design of a building. The student design team is mentored by practitioners from industry and academia, such ARUP, Bechtel, Berkley National Labs, etc.

The structure of the GTE-course allows easy participation for the Cork students. After a one week introduction at Stanford University in mid January the students travel home and start working on the design project using a whole suit of collaboration tools. Two meetings are scheduled per week and supported by videoconferencing and application sharing. In early May students return to Stanford and present their final design solution to mentors and lecturers from all participating Universities.

5.2 *ERASMUS*

The ERASMUS programme of the European Union is a well established, formalized framework programme to stimulate student and teacher exchange within the EU. Under this framework each University signs bilateral agreements with partner universities in member states or associated member states of the EU.

In terms of student mobility students agree with their lecturers on a dedicated set of modules to be taken at the partner university. The EU compensates on a moderate level for travel and other costs related to the stay abroad. In terms of teacher mobility lecturers agree in advance on the lectures they deliver at the host institution. The EU compensates on a moderate level for travel and other costs related to the stay abroad.

The modular course structure of our programme, the jointly agreed "Course Pool" and the capability for remote teaching strongly support the participation in the ERASMUS programme.

6 CONCLUSIONS

Since 2006 more than 40 students have been enrolled in the MEngSc programme on "Information Technology in AEC". As per December 2009 17 students graduated from the programme and another cohort of 17 students is currently finishing their Master Thesis and will be eventually conferred in December 2010.

Within the past three years five students received a scholarship sponsored by industry partners or National funding agencies. Six graduates progressed as PhD students, five at University College Cork and one at Trinity College, Dublin. So far, all graduates went back into employment and could clearly benefit from the knowledge and expertise acquired in the programme.

Eleven guest lecturers from five different European countries contributed outside of Ireland contributed to the programme.

In summary, the programme could be considered as a success story and has developed a clear track record over the past four Academic Years.

7 FUTURE WORK

It with great pleasure that we can report that the programme became the "role model" for the etablishment of a second programme of this type in Ireland; a joint initiative of the Irish Construction Information Technology Alliance (CITA) and Dublin Institute of Technology (DIT). This launch clearly demonstrates that there is a need for an "IT-profile in the construction sector.

Major contributors to both programmes in Cork and Dublin are the two Slovenian partner Universities, the University of Maribor and the University of Ljubljana. The exploitation of the synergy effects of the ITC-Euromaster Course

Pool becomes more visible and stronger through these new collaborations.

In terms of the development of our technological basis UCC and the University of Maribor have joined forces and both academic institutions have agreed to operate two independent AdobeConnectpro Servers. Through the joint usage of the two servers lecturers and students can share experiences and collectively develop new skills. Additionally, the programme delivery becomes more stable and robust, since a backup solution can be easily provided if required.

Finally, we plan to further develop our course material and to better exploit the potentials of the course portal, especially the options for the joint development of glossaries, the options to easier share intermediate results and to collect feedback from students.

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Outline of a schema for network-based space layouts

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ABSTRACT: A schema is outlined which uses a network approach to represent fine-grained layouts of architectural spaces. Such layouts could be useful in building design and building operation, where applications with access to space configuration data could provide improved or novel services. The schema is influenced by existing architectural space schemas. It covers spaces, space boundaries, and space elements such as enclosure, furnishing, and equipment elements. The main data structure in a layout is a layout element network. It represents certain topological relationships which are mostly derived from layout element geometry data.

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1 INTRODUCTION

In the space planning domain, networks are used to represent and analyze topological and geometric properties of schematic space layouts (see, for example, March and Steadman 1974, Hillier and Hanson 1989). Nodes in these networks typically represent spaces or walls, while weighted, directed edges that connect nodes represent adjacency relationships, dimensions, or distances. In this paper, the network approach is applied to the representation of more fine-grained layouts which include space boundary and space elements. Space enclosure, furnishing and equipment elements are examples of space elements. Such network-based space layouts could be useful in building design as well as building operation. For instance, smart lighting control or indoor navigation applications may access space configuration data in network-based space layouts to provide improved or novel services that are more responsive to the needs of individual building users. Increasingly, required sensor, actuator, and distributed computing technologies are available to enable such services (Mahdavi et al. 2009, Brambley et al. 2005, Kaasinen 2001, Streitz et al. 2001).

A schema for network-based space layouts is described which is influenced by existing space schemas (see, for example, Björk 1992, Eastman and Siabiris 1995, Ekholm and Fridqvist 2000). These schemas address the space representation problem from two views. The first is a space-centered view where a space is seen as an object which encloses a void and enables activities. A space is bounded by space boundaries which are formed by enclosing elements such as walls, floors, ceilings, and openings. The second view is construction-centered and emphasizes the arrangement of space separating physical structures. According to that view, space may be seen as a shared, emergent property of an aggregate of physical structures (Ekholm and Fridqvist 2000). Comprehensive space schemas aim to reconcile both views.

A rationale for the design of the proposed schema is given in the next section. The schema consists of two complementary subschemas: a layout element network schema (Section 3), which models layout elements and certain topological relationships between them, and a geometry schema (Section 4). Examples are provided to illustrate the structure and potential utility of network-based space layouts (Section 5). Limitations of the schema and future work are discussed (Section 6).

2 SCHEMA DESIGN CONSIDERATIONS

The proposed schema adopts a space-centered view. In addition to spaces, space boundaries, and space enclosures, it covers space related furnishing and equipment elements. The latter include sensors, actuators, luminaires, and air inlets or outlets. These space elements are relevant to building services domains. Only equipment elements that directly interface with spaces are of interest. That is, ducts or plants, which do not directly interact with spaces, are assumed in separate models.

The representation of space enclosures is simplified. For example, holes in walls which are filled by doors or windows are not explicitly modeled.

Similarly, there is no support for space enclosure decomposition. These features are required for construction-centered space models.

Layout elements and certain topological relationships between them are represented by a geometric network. This network facilitates queries such as shortest path or nearest neighbor queries. Shortest path queries are useful, for example, in the indoor navigation domain to identify feasible routes between a source and a destination space. Likewise, in an open-plan office, a lighting agent, which optimizes lighting conditions for a user, may use nearest neighbor queries to determine those windows, shades, luminaires, and furnishing elements which are near the user's desk. Moreover, these queries are useful to derive network weights. As will be shown, sublayouts may be selected from layouts based on network weight filters (Section 5).

Multiple layouts may be required to model domain-specific spatial sub-systems. For example, there may be lighting control, climate control, or circulation layouts at various abstraction levels. New layouts may be derived from existing ones, or layouts may be related to each other. In this paper, however, the objective is to first define the structure of individual layouts. For similar reasons, aggregation relationships are not included in the proposed schema. Some may be derived from other topological relationships, or the schema may be extended, for example, to support aggregation relationships between layouts.

In existing space schemas, geometry representation is less of an issue because topological relationships are explicitly modeled. Mechanisms are assumed to maintain consistency between geometrically implied and explicit relationships.

By contrast, an existing geometry schema is assumed in this layout schema to represent the shapes of layout elements. Although the commitment to a particular geometry representation method may limit the generality of the layout schema, there are at least two benefits. First, certain topological relationships may be formally defined based on geometry data (see Appendix). With these definitions, it is feasible to more comprehensively check the consistency of layouts and hence improve layout data quality. Second, most topological relationships may be derived automatically from geometry data, thereby minimizing manual effort to create layouts. This is significant because relationships may be difficult to identify manually and typically by far outnumber layout elements.

3 LAYOUT ELEMENT NETWORK SCHEMA

3.1 *Layout elements and relations*

A layout has a layout element network which consists of layout elements (*le* s) and layout relationship elements (*lr* s). The former include spaces, space boundary and space elements. *Le* s and *lr* s are instances of, respectively, the (abstract) LayoutElement and LayoutRelationship classes. A Unified Modelling Language (UML) class diagram of the *le* network is shown in Figure 1 (Jacobson et al. 1998).

A *le* network is a geometric network where each *le* node has a position in three-dimensional space, and each *lr* edge has a length which may, for instance, correspond to the air distance between a pair of nodes. Moreover, *le* s and *lr* s have a generic weight attribute. Weight derivation operations

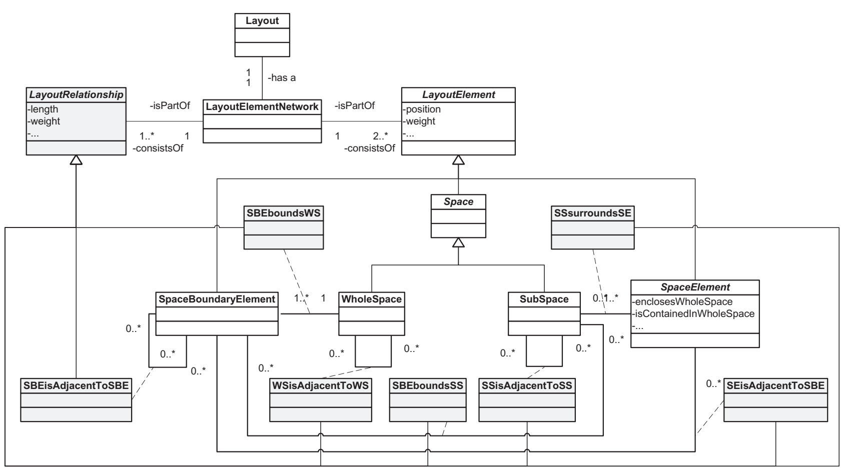


Figure 1. Layout element network schema.

may assign values to these numeric attributes (Section 5). Since *lr* s have attributes, the concrete sub-classes of the LayoutRelationship class are modeled as association classes.

3.2 *Spaces*

An architectural space may be defined as a volume which enables activities and typically accommodates people (Björk 1992, Ekholm and Fridqvist 2000, BuildingSmart 2007). Similar to existing schemas, a distinction is made between whole spaces and subspaces, which are also referred to in the literature as, respectively, spaces and partial spaces. There are three major differences between whole spaces and subspaces in this schema:

1. A subspace must be contained in a whole space (Appendix A.9). Conversely, a whole space must not be contained in any other space in the same layout.
2. A whole space must be completely bounded by space boundary elements. Conversely, a subspace may be completely bounded, partially bounded, or unbounded, as defined in Space boundary elements.
3. While whole spaces must not overlap, subspaces that are contained in the same whole space may overlap. Moreover, subspaces may or may not fill the volume of the containing whole space.

Due to these and additional differences, as described below, whole spaces and subspaces are modeled as separate classes. The aggregation relationship between whole spaces and subspaces is not included explicitly in the schema but may be derived from other relationships. Moreover, recursive space decomposition within a layout (e.g. of buildings into floors, rooms, and zones in rooms) is not supported. As mentioned in Section 2, this could be addressed by multiple layouts with aggregation relationships between spaces in different layouts.

The void enclosed by a space is approximated by a volume. It is an approximation because the arrangement of volumes in a layout ignores the thicknesses of space enclosures. Space volumes are considered as solids and represented by a boundary representation (Brep) data structure (geometry Schema). The position of a space corresponds to a point in the interior of its volume. That point may be an approximation of the volume's center, or, as in case of a subspace, it may be defined relative to the space element which the subspace surrounds.

A pair of whole spaces are adjacent if at least one pair of volume faces overlap (Appendix A.3). Although the adjacency relationship between whole spaces is redundant, that is, it may be derived from other relationships, it is modeled explicitly because of its relevance.

Similarly, a pair of subspaces are adjacent if their volumes overlap, or at least one pair of volume faces. Moreover, both subspaces must be contained in the same whole space (Appendix A.4). For example, in the circulation domain, considering subspaces contained in different whole spaces as adjacent would be undesirable owing to obstructing space enclosures.

3.3 *Space boundary elements*

A space boundary element (*sbe*) is a part of the immaterial layer which delimits a space. Its geometry corresponds to a whole space volume face. The position of an *sbe* is a point in the interior of that face. Its normal is the face normal at that point (Appendix A.10).

An *sbe* does not only bound a whole space (Appendix A.5), but may also bound multiple subspaces (Appendix A.6). The latter relationship is derived by identifying pairs of overlapping whole and subspace volume faces and applying additional conditions.

As mentioned, a whole space must be completely bounded by *sbe* s. That is, there must be an *sbe* for each whole space volume face. There are three situations for subspaces:

1. If the whole space contains a subspace with equivalent volume, then the subspace is considered to be completely bounded. In that case, there is an *sbe* for each face of the subspace volume.
2. If the whole space contains a subspace with different volume, and if at least one face of the subspace volume is related to an *sbe*, then the subspace is considered to be partially bounded.
3. If the whole space contains a subspace with different volume, and if no face of the subspace volume is related to an *sbe*, then the subspace is considered to be unbounded.

In addition to bounding spaces, an *sbe* may optionally be adjacent to other *sbe* s and certain space elements, as described in Section 3.4. Adjacencies between *sbe* s are defined independent of the space enclosure (Appendix A.7). Thus layouts with incomplete space enclosure data are feasible. This flexibility appears desirable as complete space enclosure data may not be available or required. For example, the indoor navigation domain requires data about openings which provide access to spaces but not necessarily the walls in which the openings are contained.

3.4 *Space elements*

Space enclosure, equipment, and furnishing elements are examples of space elements (*se* s).

The respective SpaceElement class is an abstract class. Its subclasses are not shown in Figure 1. Topological relationships in a layout that involve *se* s are defined independent of *se* sub-class membership.

The SpaceElement class has attributes which designate an *se*'s role as either contained in or enclosing a whole space. Although there are no corresponding explicit relationships in the schema, predicates on these attributes are used to define other topological relationships involving *se* s. Whereas the role of an *se* is typically unambiguous, a cabinet *se* may enclose a whole space in one context and be contained in a whole space in another. In contrast to corresponding single-inheritance extensions of the SpaceElement class, the attribute-based approach provides the flexibility to account for *se* s which can assume both roles.

An *se* may be surrounded by subspaces. For example, a window *se* can be viewed as being surrounded by a subspace which is contained in a whole space. The subspace can be thought of as a natural lighting zone. Similarly, a free-standing cabinet *se* can be viewed as being surrounded by (or accessed by) subspaces and sub-dividing the containing whole space. Default subspaces may be defined relative to *se* s in *se* product libraries, which facilitates the creation of space layouts.

Whole space contained and whole space enclosing *se* s have different constraints regarding their relationships to subspaces. A whole space contained *se* must be surrounded by at least one subspace because it would otherwise be isolated in the *le* network. This would complicate operations such as the retrieval of whole spaces and related *se* s. Conversely, a subspace can not exist without surrounding at least one *se*. Relationships to subspaces are optional for a whole space enclosing *se*. For example, wall *se* s may or may not be surrounded by subspaces. On the other hand, a whole space enclosing *se* must be adjacent to at least one *sbe*. The definition of this relationship depends in part on available *se* geometry data (Appendix A.8, Appendix A.11). If an *se* is part of the enclosure of one or two whole spaces and thus is adjacent to one or two *sbe* s, as is typically the case for opening *se* s, it is sufficient to match the *se* position and normal with whole space faces.

However, in case of a wall *se* more detailed geometry data is required because it may be adjacent to more than two *sbe* s. Consequently, the shape of an *se* may optionally be represented by a face, which is matched with whole space faces to correctly identify all adjacencies to *sbe* s.

4 GEOMETRY SCHEMA

A solid boundary representation (Brep) schema is assumed to represent space, *sbe*, and *se* shapes (Figure 2). Breps are widely used in solid modelling systems. Ideally, a solid Brep schema covers linear and curved as well as simple and non-simple polygons and polyhedra. The ISO 10303-42:2003 standard defines a comprehensive solid Brep schema, which is also used by IFC (ISO 2003, BuildingSmart 2007).

5 EXAMPLES

The structure of network-based space layouts is illustrated with examples (Figures 3–5). The examples also show how useful topological properties can be derived from network-based space layouts.

As layouts are difficult to visualize as a whole, in each example a sublayout is selected from the same original layout. Sublayouts are selected and weights of their *le* nodes derived as follows:

1. P_{LE} and P_{LR} filters are used to select a sublayout from the original layout. A P_{LE} filter is a list of predicates on *le* s in a layout, a P_{LR} filter likewise on *lr* s. Geometry data associated with *le* s are implicitly selected as well.
2. A subset of *le* s in the sublayout are selected by a third filter, P_S. These are source nodes for nearest neighbor queries on the sublayout's *le*

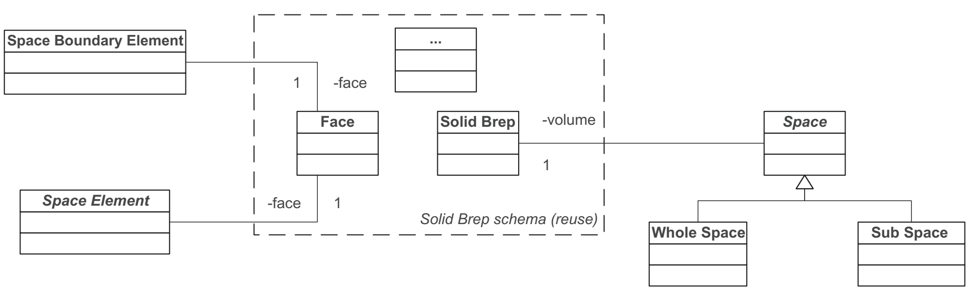
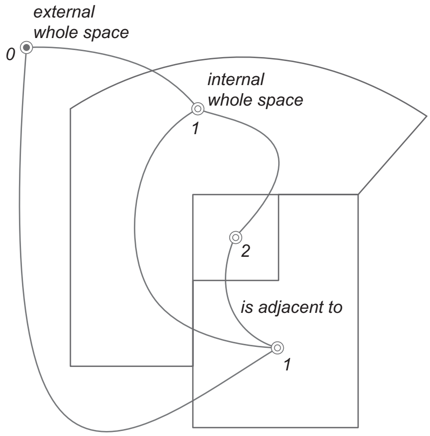
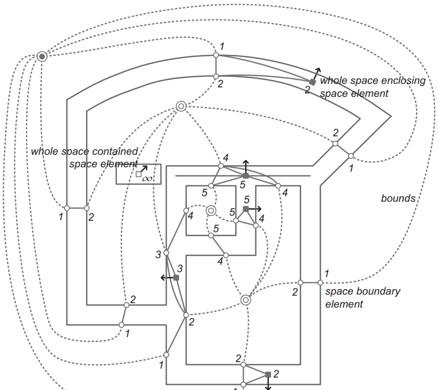


Figure 2. Geometry schema.



$$P_{LE} = {}_*(WS),\ P_{LR} = {}_*(WSisAdjacentToWS)$$
$$P_S = {}_*(WS),\ P_D = {}_{\neg isInternal}(WS)$$

Figure 3. Sublayout selected from the original layout based on P_{LE} and P_{LR}. Node weights are derived based on P_S and P_D.



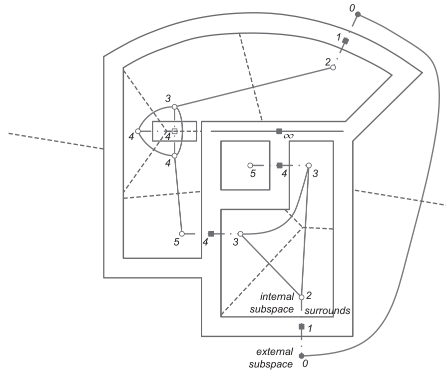
$$P_{LE} = ({}_*(WS),\ {}_*(SBE),\ {}_*(SE))$$
$$P_{LR} = ({}_*(SBEboundsWS),\ {}_*(SBEisAdjacentToSE),\ {}_*(SBEisAdjacentToSBE))$$
$$P_S = ({}_*(SBE),\ {}_*(SE)),\ P_D = {}_{\neg isInternal}(WS)$$

Figure 4. Sublayout selected from the original layout.

network. Destination nodes are selected by a fourth filter, P_D. A nearest neighbor query is performed for each source node.

3. For each source node, the weight of the path to its nearest neighbor node is assigned to its weight attribute. This is done after all queries have been processed.

In the original layout, all *le* and *lr* weights are assumed to be, respectively, zero and one. An



$$P_{LE} = ({}_*(SS),\ {}_*(SE))$$
$$P_{LR} = ({}_*(SSisAdjacentToSS),\ {}_*(SSsurroundsSE))$$
$$P_S = ({}_*(SS),\ {}_*(SE)),\ P_D = {}_{\neg isInternal}(SS)$$

Figure 5. Sublayout selected from the original layout.

isInternal attribute is assumed for the Space class, which indicates if a space is internal or external. In all examples, external spaces are targeted by P_D. For clarity, only parts of the boundaries of external space volumes, which are finite, are shown in Figures 3–5.

Filters are defined using the following notation: predicates appear in subscript, and the class of targeted *le* s or *lr* s in parenthesis. An asterisk means all *le* s or *lr* s of a class in a layout, a ¬ symbol negation.

In the first example, only whole spaces and *WSisAdjacentToWS* relationship elements are selected by P_{LE} and P_{LR} from the original layout (Figure 3). The distance to the nearest external whole space is computed for each whole space in the selected sublayout. In a subsequent selection operation on the sublayout with modified weights, only those whole spaces may be selected whose weights are equal to one. In other words, the selected whole spaces would be internal and adjacent to the building's perimeter. The distinction between internal perimeter and non-perimeter spaces is relevant for thermal and lighting domains. In the second example, a sublayout is selected from the same original layout. In addition to whole spaces, the sublayout includes *sbe* s and *se* s (Figure 4). Space volumes are offset in the figure to better visualize adjacency relationships involving *sbe* s and *se* s; space volumes may actually touch, as shown in Figure 3. Most whole space enclosing *se* s are door *se* s which are adjacent to two *sbe* s. By contrast, there is one wall *se* which is adjacent to three *sbe* s. Its face geometry is required to correctly derive these adjacencies.

Sbe s and *se* s are selected by P_S, and external whole spaces by P_D. As a result, *se* s and *sbe* s with a weight of two can be considered as being part of, respectively, the building enclosure and its internal boundary. Again, such information is relevant for thermal and lighting domains.

The last example involves a circulation view of the original layout (Figure 5). The sublayout selected by P_{LE} and P_{LR} consists of subspaces and *se* s as well as respective adjacency and surround relationships. In the original layout, one subspace is completely and all others are partially bounded. There is no unbounded subspace. A set of subspace volumes that are contained in a whole space is derived in two steps. First, Voronoi cells are created from the set of subspace positions. Second, each cell is intersected with the whole space volume to ensure that it is fully contained in that volume.

In the circulation domain, Voronoi cell based subspace volumes appear useful because, by the air distance measure, any position contained in a subspace volume is nearer to the subspace's position than to the position of any other subspace that is contained in the same whole space. Moreover, Voronoi cell based subspace volumes fill the volume of the containing whole space. As a result of both properties, any location in a whole space can easily be associated with its nearest subspace node, which may be a source or destination node in a navigation query on the *le* network. Subspace volumes which do not fill their whole space volumes or overlap with each other are also supported by the schema but not present in this example.

Subspaces and *se* s are selected by P_S, and external subspaces by P_D. The distance from the deepest subspaces to the nearest of the two external subspaces is five. Other depth-related properties of individual subspaces or the sublayout as a whole, such as mean depth or relative asymmetry, may be derived from the *le* network (Hillier and Hanson 1989).

Assuming that there are attributes which indicate if a subspace adjacency edge crosses an *se*, as is the case for the cabinet *se*, then P_{LR} may be adjusted to select only obstruction-free adjacency edges. This would result in a more accurate circulation view.

6 CONCLUSION

Several issues related to the schema will be examined by future work in this on-going research effort. The first issue is to check if a given layout, or a sublayout selected from a layout, is topologically consistent. Topological consistency is particularly relevant for network-based space layouts because topological relationships are represented explicitly in the *le* network as well as implied by *le* geometries. To that end, additional topological constraints need to be defined. An example is a constraint that whole space volumes must not overlap. The second issue is to transform an inconsistent layout into a consistent one. For example, inconsistent, whole space contained *se* s may be removed from a layout. The third issue concerns the comparison of layouts. That is, conditions for the equivalence of *le* s need to be established. Once these extensions are defined, the next steps are to implement the schema in a spatial database and to define operations to create and modify network-based space layouts.

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APPENDIX DEFINITION OF TOPOLOGICAL RELATIONSHIPS

A.1 *Introduction*

Certain topological relationships that are implied by *le* geometry data are defined in this Appendix. Some of these relationships are represented explicitly in a layout's *le* network (Figure 1). Others are not represented explicitly but used in the definition of explicitly represented relationships. With the exception of the *SSsurroundsSE* relationship, all topological relationships in a *le* network are implied by *le* geometry data.

A.2 *Layout element and geometric object sets*

The LayoutElement set, its subsets, and certain geometric object sets provide the context (domain of discourse) for the definition of topological relationships.

Let $LEN(A)$ be a network-based space layout of a configuration A of spaces, space boundary and space elements, and $LE = layoutElements(LEN(A))$ the set of *le* s in $LEN(A)$.

The following are subsets of LE:

- the set of whole spaces
  $WS = \{ws_1, ws_2, \ldots, ws_n\}$
  $= wholeSpaces(LEN(A))$
  $= \{le | le \in LE \wedge classOf(le) = \text{'WholeSpace'}\}$,
- the set of subspaces
  $SS = \{ss_1, ss_2, \ldots, ss_m\}$
  $= subSpaces(LEN(A))$
  $= \{le | le \in LE \wedge classOf(le) = \text{'SubSpace'}\}$,
- the set of *se* S
  $SE = \{se_1, se_2, \ldots, se_0\}$
  $= spaceElements(LEN(A))$
  $= \{le | le \in LE \wedge classOf(le) = \text{'SpaceElement'}\}$, and
- the set of *sbe* s
  $SBE = \{sbe_1, sbe_2, \ldots, sbe_p\}$
  $= spaceBoundaryElements(LEN(A))$
  $= \{le | le \in LE \wedge classOf(le) = \text{'SpaceBoundaryElement'}\}$.

Sets of geometric objects are defined with respect to LE subsets:

- the set of whole space volumes
  $WSV = \{wsv_1, wsv_2, \ldots, wsv_n\} = volumes(WS)$,
- the set of subspace volumes
  $SSV = \{ssv_1, ssv_2, \ldots, ssv_q\} = volumes(SS)$,
- the set of whole space volume faces
  $WSF = \{wsf_1, wsf_2, \ldots, wsf_p\} = faces(WSV)$, and
- the set of subspace volume faces
  $SSF = \{ssf_1, ssf_2, \ldots, ssf_k\} = faces(SSV)$.

A.3 *WSisAdjacentToWS relationship*

Definition:
$isAdjacentTo \subset WS \times WS = \{(ws_1, ws_2) | ws_1 \in WS \wedge ws_2 \in WS \wedge ws_1 \# ws_2 \wedge$
$\exists wsf_1 \in WSF, \exists wsf_2 \in WSF, \exists wsv_1 \in WSV, \exists wsv_2 \in WSV(overlaps(wsf_1, wsf_2) \wedge bounds(wsf_1, wsv_1) \wedge bounds(wsf_2, wsv_2) \wedge wsv_1 = volume(ws_1) \wedge wsv_2 = volume(ws_2))\}$
Comments: Self-adjacency is excluded.

Boolean overlaps(face a, face b) is a geometric modelling function. Two faces overlap if the intersection of their interiors is non-empty.

The *WSFboundsWSV* relationship is a subset of the *FboundsV* relationship in the solid Brep schema (Figure 2). It is either explicit or derived.

A.4 *SSisAdjacentToSS relationship*

Definition:
$isAdjacentTo \subset SS \times SS = \{(ss_1, ss_2) | ss_1 \in SS \wedge ss_2 \in SS \wedge ss_1 \neq ss_2 \wedge$
$\exists ssf_1 \in SSF, \exists ssf_2 \in SSF, \exists ssv_1 \in SSV, \exists ssv_2 \in SSV,$
$\exists ws \in WS (((overlaps(ssv_1, ssf_2) \wedge$
$bounds(ssf_1, ssv_1) \wedge bounds(ssf_2, ssv_2)) \vee$
$overlaps(ssv_1, ssv_2)) \wedge$
$ssv_1 = volume(ss_1) \wedge ssv_2 = volume(ss_2) \wedge$
$contains(ws, ss_1) \wedge contains(ws, ss_2))\}$

Comments: Self-adjacency is excluded. A pair of subspaces are adjacent if their volumes overlap, or at least one pair of volume faces, and if they are contained in the same whole space. Volumes that touch only at edges or vertices are not considered as adjacent.

Boolean overlaps(*face a, face b*) is a geometric modelling function.

Boolean overlaps(*solidBrep a, solidBrep b*)is a geometric modelling function. Two solid Breps overlap if the intersection of their interiors is non-empty.

The *SSFboundsSSV* relationship is a subset of the *FboundsV* relationship in the solid Brep schema.

The *WScontainsSS* relationship is defined in Appendix A.9.

A.5 *SBEboundsWS relationship*

Definition:
$bounds \subset SBE \times WS = \{(sbe, ws) | sbe \in SBE \wedge ws \in WS \wedge \exists wsf \in WSF, \exists wsv \in WSV($
$contains(wsf, sbe) \wedge bounds(wsf, wsv) \wedge wsv = volume(ws))\}$
Comments: The *WSFcontainsSBE* relationship is defined in Appendix A.10.

The *WSFboundsWSV* relationship is a subset of the *FboundsV* relationship in the solid Brep schema.

A.6 *SBEboundsSS relationship*

Definition:
$bounds \subset SBE \times SS = \{(sbe, ss) | sbe \in SBE \wedge ss \in SS \wedge \exists ssf \in SSF, \exists ssv \in SSV, \exists wsf \in WSF, \exists wsv \in WSV,$
$\exists ws \in WS(overlaps(ssf, wsf) \wedge contains(wsf, sbe) \wedge bounds(ssf, ssv) \wedge bounds(wsf, wsv) \wedge ssv = volume(ss) \wedge wsv = volume(ws) \wedge contains(ws, ss))\}$
Comments: Boolean overlaps(face a, face b) is a geometric modelling function.

The *WSFcontainsSBE* relationship is defined in Appendix A.10.

The *WSFboundsWSV* and *SSFboundsSSV* relationships are subsets of the *FboundsV* relationship in the solid Brep schema.

The *WScontainsSS* relationship is defined in Appendix A.9.

A.7 *SBEisAdjacentToSBE relationship*

Definition:
$isAdjacentTo \subset SBE \times SBE = \{(sbe_1, sbe_2)|\ sbe_1 \in SBE \wedge sbe_2 \in SBE \wedge sbe_1 \# sbe_2 \wedge \exists wsf_1 \in WSF, \exists wsf_2 \in WSF($
$overlaps(wsf_1, wsf_2) \wedge$
$contains(wsf_1, sbe_1) \wedge contains(wsf_2, sbe_2))\}$
Comments: Self-adjacency is excluded.

Boolean overlaps(face a, face b) is a geometric modelling function.

The *WSFcontainsSBE* relationship is defined in Appendix A.10.

A.8 *SEisAdjacentToSBE relationship*

Definition:
$isAdjacentTo \subset SE \times SBE = \{(se, sbe)|se \in SE \wedge sbe \in SBE \wedge$
$encloseWholeSpace(se) \wedge$
$\exists wsf \in WSF(isAdjacentTo(se, wsf) \wedge contains(wsf, sbe))\}$
Comments: The relationship is only defined for *se* s that are designated as whole space enclosing.

The *SEisAdjacentToWSF* relationship is defined in Appendix A.11.

The *WSFcontainsSBE* relationship is defined in Appendix A.10.

A.9 *WScontainsSS relationship*

Definition:
$contains \subset WS \times SS = \{(ws, ss)|ws \in WS \wedge ss \in SS \wedge \exists wsv \in WSV(wsv = volume(ws) \wedge$
$contains\ (wsv, position(ss)))\}$
Comments: This relationship is not explicitly represented in the *le* network schema.

Boolean contains(solidBrep a, point p) is a geometric modelling function. The relationship is defined with respect to subspace positions. The relationship may thus be derived without knowing subspace volumes.

A.10 *WSFcontainsSBE relationship*

Definition:
$contains \subset WSF \times SBE = \{(wsf, sbe)|wsf \in WSF \wedge sbe \in SBE \wedge$
$contains(wsf, position(sbe)) \wedge normal(wsf, position(sbe)) = normal(sbe)\}$
Comments: This relationship is not explicitly represented in the *le* network schema.

Normals of *wsf* and *sbe* must point in the same direction. Without this condition, there would be incorrect matches.

Boolean contains(face a, point p) is a geometric modelling function. *P* must lie on the interior of *a*.

Vector normal(face a, point p) is a geometric modelling function. It returns the normal of *a* at *p*.

A.11 *SEisAdjacentToWSF relationship*

Definition:
$isAdjacentTo \subset SE \times WSF = \{(se, wsf)|se \in SE \wedge$
$encloseWholeSpace(se) \wedge wsf \in WSF \wedge$
$isPerpendicular((position(se), normal(se)), wsf)) \wedge$
$dist(position(se), wsf) < tol \wedge$
$(face(se) = \emptyset \vee overlaps(wsf, project(face(se), surface(wsf))))\}$
Comments: The relationship is not explicitly represented in the *le* network schema. It is only defined for *se* s which are designated as whole space enclosing.

For an *se* to be considered as adjacent to a *wsf*, it does not necessarily need to lie in the same surface in which a *wsf* is embedded, but only reasonably close, provided that the other conditions are met as well. As space volumes are only approximated, this situation is common and thus needs to be addressed.

Two situations regarding *se* geometry data are distinguished:

1. If only *se* position and normal are available, then the relationship is determined based on that data only. However, position and normal are not sufficient for the general case where a *se* (e.g. a wall *se*) is adjacent to more than two whole space faces (see Figure 4 for an example).
2. If the face of the *se* is known in addition to *se* position and normal, it is possible to derive the relationship correctly also for the general case where a *se* is adjacent to more than two whole space faces.

Boolean isPerpendicular ((point p, vector d), face a) is a geometric modelling function which determines if line *(p,d)* is perpendicular to face *a*. That is, *d* must be parallel to the normal of the surface of *a* at point *p'*, which is the projection of *p* to the surface of *a* based on *d*. If *p'* does not lie on *a*'s interior, then false is returned.

Real dist((point p, vector d), face a) is a function that determines the distance between *p* and the surface of *a* based on the projection direction *d*.

Face project(face a, surface b) is a function that returns a face, which is obtained by projecting *a* to *b*.

Surface surface(face a) is a geometric modelling function that returns the surface in which *a* is embedded.

Boolean overlaps(face a, face b) is a geometric modelling function.

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Visual design with the use of graph-based data structure

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ABSTRACT: In the Internet age designers rely on CAD tools to amplify their mental abilities. Nowadays detailed design and documentation phases of the design process are well supported by CAD systems. The conceptual design phase, however, still lacks satisfactory knowledge-based design systems. This paper aims at contributing to a better understanding of conceptual design with computer tools. Coming up to designers' expectations this paper proposes new automatic methods of storing up design knowledge and design reasoning during the presentation of early design solutions in the form of drawings on the monitor screen. The presented methods are based on graph transformations and first order logic. A useful starting point for these methods is a visual language allowing the designer to visualize both design solutions and some specification of requirements. To generalize the proposed methods the two types of designing: functional and form-oriented are discussed. In the former, the design drawings are automatically transformed into appropriate elements of the graph-based data structure and then information stored in the data structure is translated to formulas of the first-order logic, which constitute design knowledge. In the latter, graph-based data structure is less complex and information retrieved from the structure gives less formulas for design knowledge. The results we obtain allow one to implement a prototypical CAD system with the intelligent computer modules supporting conceptual design.

Keywords: conceptual design, graph transformations, first order logic, visual language, graph-based data structure, CAD system

eg-ice invited paper, european group for intelligent computing in engineering

1 INTRODUCTION

During the conceptual phase of design process, designers operate at a very high level of abstraction. To construct knowledge-based design systems supported conceptual design the representation and manipulation of knowledge in computers is needed (Coyne et al. 1990). Graph methods integrating the representation of the designed objects and the process of generation of their models appear then very often. While data structure is represented by graphs, graph grammars provide a formalism to express the description, generation and manipulation of graphs. Graph grammars enable to model complex graph transformations formally and to specify infinite classes of graphs with the same inherent syntactic structure compactly (Rozenberg, 1999).

Graph transformations are useful for specification, modelling and prototyping of knowledge based design tools in Civil Engineering, in particular for the conceptual phase of design. They can describe the functionality and decomposition of designed objects, for instance in function-structure editors generating graph structures of designed objects on the base of functional graphs (Borkowski & Grabska, 1998). In the graph knowledge representation the way of organization, processing and manipulation of knowledge is based on the spatial relations between objects (Nagl, 1996).

Graphs can be combined with the most popular logic –based knowledge representation techniques, where knowledge is represented explicitly by symbolic terms and reasoning is the manipulation of these terms. GraCAD (Szuba 2005) developed with the use both of PROGRES (PROgrammed Graph Rewriting System) (Schuerr et al. 1995) and ARCHICAD is an example of graph computer tools supporting conceptual design and connecting graph and logic methods. In the GraCAD, use cases and scenarios as well as design requirements and constraints are specified by graph structures.

The most common starting point for conceptual design is designers' dialogue with some medium (paper, monitor screen) where design concepts can be visualized. The designer usually begins with doing sketches. Contemporary specialized CAD tools allow him/her to replace sketches by visualizing general ideas about projects on the monitor screen. Nowadays designers can use visual languages during the design process. When developing a visual language the role of sketches in the conceptual design was taken into consideration (Goldschmidt, 1991). Elements of the visual language are not treated as completed designs (Ware 2008). They play a role of sketches but are created with the use of an appropriate computer editor. Using a visual language in the phase of conceptual design characterizes so called *visual design* (Grabska 2007).

This paper connects visual design with graph methods. Both type of visual designing: functional and form-oriented are discussed. In the former, drawings created by the designer on the monitor screen are automatically transformed into appropriate elements of the graph-based data structure. Information stored in the data structure are translated to symbolic type of knowledge representation, where formulas of the first-order logic allow one to reason about individuals in design domain and properties that they have (Fagin et al. 2003). In the latter, graph-based data structure is less complex and information retrieved from the structure provides less formulas for design knowledge.

The proposed approach gives a base for equipping the design interface with the intelligent assistant supporting conceptual design by reasoning about the design features and suggesting design modifications. The prototype editor in the design supporting system was described in (Grabska et al. 2008). The first implementation of the system *HGSDR* (Hypergraph Generator Supporting Design and Reasoning) was presented in (Grabska et al. 2009). In this paper some components of *HGSDR* system will be sketched to illustrate a layout visual language, which enables the designer to create and edit floor layouts.

2 VISUAL LANGUAGES

The process of conceptual design takes place at various levels of abstraction. The most common way is to start with a design using general concepts. Usually the designer begins with doing sketches in search of shapes and relations among them. Almost half the brain is devoted to the visual sense and the visual brain is capable of interpreting visual objects in many different ways. Therefore sketching is one of the best ways to absorb design ideas. But in the Internet age the designer uses also a visual language and he/she creates drawings on the monitor screen by means of an appropriate CAD tool.

A visual language is characterized by a *vocabulary* being a finite set of basic shapes and a finite set of *rules* specifying possible configurations of these shapes, which are elements of the language.

CAD editors, i.e. tools used by the designers for generating visual language elements are divided into two-dimensional and three-dimensional. Using 2D CAD editors, designers draw with basic shapes like lines, polygons, circles, etc. In the case of 3D CAD tools, the vocabulary of basic forms contains for instance: cubes, spheres, cylinders, pyramids, etc.

CAD editors are also divided into *general* and *specialized*. General CAD editors allow designers of various specialties to create drawings/designs. These tools contain basic rules specifying possible configurations of shapes or forms. They do not support design elements specific for a particular design domain (like walls for building design). Such domain specific design components are supported by specialized CAD editors used by a specific group of designers. There exists a set of constraints defined for a specialized editor, which contain syntactic knowledge about design solutions. These constraints governs the design process.

3 GRAPH-BASED DATA STRUCTURE

As it has been considered graph transformations are useful for specification and modelling of design knowledge during the visual design process. The knowledge in the form of graph structures is extracted from spatial relations between components of drawings created by designers. In other words, each design drawing depicted on the monitor screen enriches design knowledge stored in the form of graph-based data structure. To represent multi-argument relations among components of the created drawing we need a specific type of graphs called *hyper-graphs* (Grabska et al. 2008).

The proposed hyper-graphs have two types of hyper-edges, called *component* hyper-edges and *relational* hyper-edges. Hyper-edges of the first type correspond to drawing components and are labeled by component names. Hyper-edges of the second type represent relations among fragments of components and can be either directed or non-directed in the case of symmetric relations. Relational hyper-edges of the hyper-graph are labeled by names of relations. Component hyper-edges are connected with relational hyper-edges by means of nodes corresponding to common fragments of connected design components (Ślusarczyk 2003).

The formal definition of hyper-graphs is as follows:

Let Σ be an alphabet of labels of hyper-edges and nodes. *An hyper-graph over* Σ is a system

$G = (E, V, t, s, lb)$, where:

1. $E = E_C \cup E_R$ is a finite set of hyper-edges, where elements of E_C, called *component hyper-edges*, represent drawing components, while elements of E_R, called *relational hyper-edges*, represent relations between drawing components.
2. V is a nonempty finite set of nodes which represent fragments of drawing components being arguments of relations.
3. $t: E \rightarrow V^*$ is a mapping assigning sequences of different *target nodes* to all hyper-edges.
4. $s: E_R \rightarrow V^*$ is a mapping assigning sequences of different *source nodes* to relational hyper-edges.
5. lb: $E \cup V \rightarrow \Sigma$ is a labeling function such that $lb(E) \cap lb(V) = \emptyset$ and $lb(E_C) \cap lb(E_R) = \emptyset$, i.e., the sets of labels of component hyper-edges, relational hyper-edges and nodes are disjoint each other.

An example of the hyper-graph over $\Sigma = \{$**S, L, G, acc, adj**) is shown in Figure 2. The labels **acc, adj** are assigned to relational hyper-edges; the remaining labels to component ones.

To represent features of design components and relations between them attributing of nodes and hyper-edges is used. Attributes represent properties (like shape, size, position, color) of elements corresponding to hyper-edges and nodes.

Let A_t be a set of attributes of hyper-edges and nodes. *An attributed hyper-graph over A_t* is a pair

$G_A = (G, att)$, where

1. G is a hyper-graph over Σ, and
2. *att:* $E \cup V \rightarrow P(A_t)$ is an *attributing function,* where $P(A_t)$ is a set of all subsets of the set A_t of attributes.

Let us consider a simplified specialized CAD editor for designing floor layout composed of polygons which are placed in an orthogonal grid. These polygons represent functional areas or rooms. Mutual location of polygons is determined by the designer. Lines with small squares on them represent the accessibility relation among components, while continuous lines shared by polygons denote the adjacency relations between them (see: Figure 1). The sides of each polygon are ordered clock-wise starting from the top left-most one. In a design drawing only qualitative coordinates are used i.e., only relations among graphical elements (walls) are essential.

Each design drawing has its internal computer representation in the form of a hyper-graph. This representation is obtained in automatic way. An example of the internal representation of the drawing presented in Figure 1 is shown in Figure 2. This hyper-graph is composed of eight hyper-edges: three component hyper-edges that correspond to the three polygons of the design drawing and

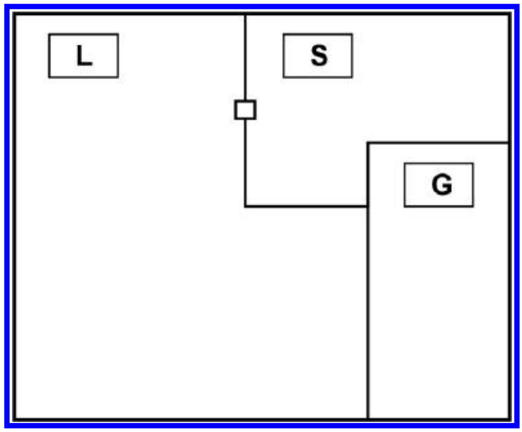

Figure 1. The design drawing with three polygons.

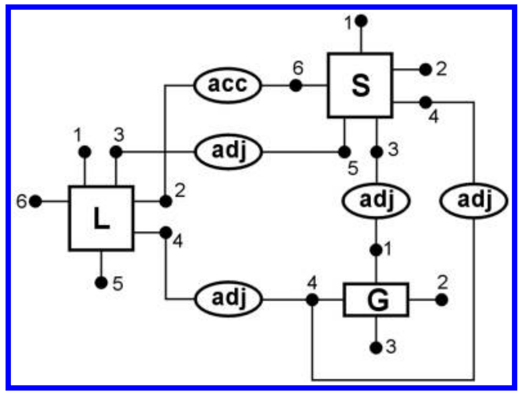

Figure 2. The hyper-graph for the drawing shown in Figure 1.

five relational hyper-edges. One of these relational hyper-edges represents the accessibility relation between two rooms corresponding to polygon L and polygon S. The remaining four hyper-edges represent the adjacency relation.

The design drawing in Figure 1 presents one of the steps of creating the layout of a one storey house with a garage. The example is very simple but its role is only to show the way of generating the hyper-graph corresponding to the design drawing edited by the designer on the monitor screen.

The example was made in the prototype system *HGSDR* (Hypergraph Generator Supporting Design and Reasoning) (Grabska et al. 2009). The system allows the designer to edit and automatically applies operations on hyper-graphs being internal representations of drawings.

Let us come back to create the design drawing presented in Figure 1. Before it is obtained, the first drawing edited by the designer represents the area of the whole apartment.

The initial hyper-graph representing this first drawing generated automatically is composed of one hyper-edge connected with four external nodes representing sides of the area and placed in the drawing according to the geographical location of the sides they correspond to. In the next step, the designer divides the whole apartment area into three parts representing a Living area (L), Sleeping area (S), and a Garage (G), respectively. Then he/she draws a small square on the line representing the common wall between the living area and the sleeping area. As a consequence, the hyper-edge operation on the initial hyper-graph is invoked automatically. As the result of this operation the hyper-graph representing the three areas and accessibility and adjacency relations between them is generated.

Each area is considered as component hyper-edges together with the nodes assigned to them.

In the considered system *HGSDR* the designer creates conceptual drawings straight on the monitor screen with the use of the editor. But this editor takes syntactic requirements related to floor-layouts into account. Moreover, the designer introduces functions of designed floor-layout during editing design drawings. This type of designing is called *function-oriented.*

Mostly, conceptual design aided by specialized CAD tools is subordinated to specify the functional requirements. The best example is using function-structure editors where the designer starts with defining a list of functions describing a design object and then generates an appropriate graph structure of this object. The consequence of function oriented design is subordinated object forms to object structures determined by functions.

4 DESIGN KNOWLEDGE

Recently, a design process is often treated as a sequence of actions, which changes the external world.

These actions called *physical design actions* consist in drawing, copying and erasing elements of graphical outputs (Suwa et al. 2000). Design actions on graphical outputs cause changes in their internal representation in the form of hyper-graphs serving as a base for reasoning about design. Design knowledge is defined in a general framework of the first-order logic.

During the design process knowledge corresponding to design drawings created by the designer is first translated to an appropriate hyper-graph and then to sentences of the first-order logic. In this process a problem-oriented relational structure, which assigns elements of hyper-graphs to entities of the specified first-order logic alphabet is used.

In first-order logic a vocabulary is defined as a triple

$A = \{C, F, R\}$, where

1. C is a set of constant symbols,
2. F is a set of multi-argument function symbols, and
3. R is a set of multi- argument relation symbols.

In our example related to design floor layout

1. constant symbols of C represent walls of rooms of a layout,
2. F contains one single argument function symbol, which determines a room to which a given wall belongs, and
3. $P = \{adj, acc\}$ is a set of relation symbols, where *adj* and *acc* are two binary relation symbols representing adjacency and accessibility between rooms.

We assume that we have a set of *variables*, which we usually write as x and y, possibly along with subscripts. The set of *terms* is formed starting from constant symbols and variables and closing off under function application, i.e., if $t_1, \ldots, t_n$ are terms and $f \in F$ is an n-ary function symbol, then $f(t_1, \ldots, t_n)$ is also a term. An *atomic formula* is either of the form $r(t_1, \ldots, t_k)$, where $r \in R$ is an k-ary relation symbol and $t_1, \ldots, t_k$ are terms, or of the form $t_1 = t_2$, where t_1 and t_2 are terms. The set of general logical formulas is built over atomic formulas using logical connectives and quantifiers, and closed under the consequence relation. The formulas contain variables universally quantified over appropriate component types. Formulas which do not have free variables are called *sentences*.

The semantics of first-order formulas uses *relational structures*. A relational structure consists of a domain of individuals and a way of associating with each of the elements of the vocabulary corresponding entities over the domain. Thus, a constant symbol is associated with an element of the domain, a function symbol and a relation symbol are associated with a function and a relation, respectively. Both function and relation are defined on the domain.

In the proposed visual design approach the relational structure is in the form of a hyper-graph corresponding to a design drawing created by the designer on the monitor screen. The domain $dom(G)$ of this structure includes:

– a set of component hyper-edges, and
– a set of hyper-graph nodes.

Relations between design components presented in the drawing are specified between fragments of these components, which correspond to hyper-graph nodes. The interpretation of each relation is the hyper-edge relation of the hyper-graph such that there is a relational hyper-edge coming from a sequence of nodes of at least one component hyper-edge and coming into a sequence of nodes of other component hyper-edges.

The next step to define the formal semantics of first-order formulas is specification of an interpretation of variables. A valuation on a structure G is a function from variables to elements of $dom(G)$. Given a relational structure G with a valuation ω on G, $(G, \omega) \models \phi$ denotes that a formula ϕ is true in G under the valuation ω.

Let us consider an example of a *direct accessibility binary relation acc* (x_1, x_2) between two rooms in the hyper-graph relational structure G.

$(G, \omega) \models acc\,(x_1, x_2)$ iff $\exists v_1, v_2 \in V$ such that $\omega(x_1) = v_1$, $\omega(x_2) = v_2$, $v_1 \in t(e_1)$, $v_2 \in t(e_2)$, where $e_1, e_2 \in E_C$ and $\exists e_3 \in E_R$ such that $v_1, v_2 \in t(e_3)$, $lb(e_3) = acc$, i.e., there exist two nodes being valuations of variables x_1 and x_2, and these nodes are assignment to different component hyper-edges and to the same relational hyper-edge labeled *acc*.

An adjacency relation *adj* (x_1, x_2) between two rooms differs from the above one only in the label of a relational hyper-edge which should be equal to *adj*.

$(G, \omega) \models adj\,(x_1, x_2)$ iff $\exists v_1, v_2 \in V$ such that $\omega(x_1) = v_1$, $\omega(x_2) = v_2$, $v_1 \in t(e_1)$, $v_2 \in t(e_2)$, where $e_1, e_2 \in E_C$ and $\exists e_3 \in E_R$ such that $v_1, v_2 \in t(e_3)$, $lb(e_3) = adj$.

Let us come back to the hyper-graph shown in Figure 2. Denote by $v_L.2$ and $v_S.6$ the node with label 2 attached to hyper-edge L and the node with label 6 attached to hyper-edge S. The atomic formula *acc* $(v_L.2, v_S.6)$ belongs to the syntactic knowledge about the designed drawing presented in Fig. 1 obtained from the relational structure being a hyper-graph corresponding to this drawing. This syntactic knowledge in the form of atomic formulas facilitate reasoning about features of designs. Moreover, changes in design knowledge resulting from drawing modifications consist in changes atomic formulas and they can be traced by the designer.

5 FORM-ORIENTED CONCEPTUAL DESIGN

Designers like experimenting with object forms. One of the best example is Opera House in Sydney. Jørn Utzon's impressive design—the sails rising into the sky—is a combination of abstraction and naturalism (Glancey 2000). Function-oriented design is against such experiments.

There exists a need to develop general CAD editors of visual languages, which could support form oriented conceptual design. Describing automatically design knowledge on the base of drawings created by the designer with the use of general CAD editors is restricted. As it has been considered the way of organization, processing and manipulation of design knowledge represented by graph structures is mainly based on the spatial relations between objects.

Let us consider an example of designing a form of private house by means of the visual language. Figure 3 presents the vocabulary of the language containing two basic figures: a cube and a cylinder, and labeled components of the designed form.

The next Figure 4 shows the initial designed form which consists of seven components being transformed basic figures or the results of Boolean operations on these figures. In this figure all components have their labels as in Figure 3.

The two views of the initial designed form in Figure 4 are presented in Figure 5 and Figure 6.

As it has been considered, the initial graph-based structure of the form-oriented conceptual design is very simple. The form structure is only determined by one binary relation of adjacency

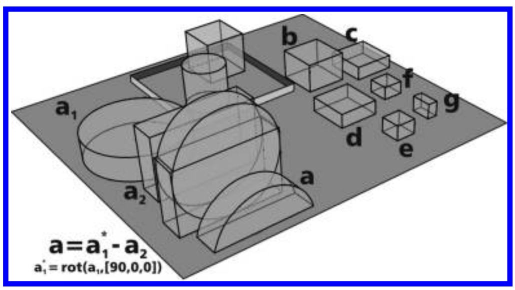

Figure 3. The vocabulary of the design language along with the labeled components of the designed form.

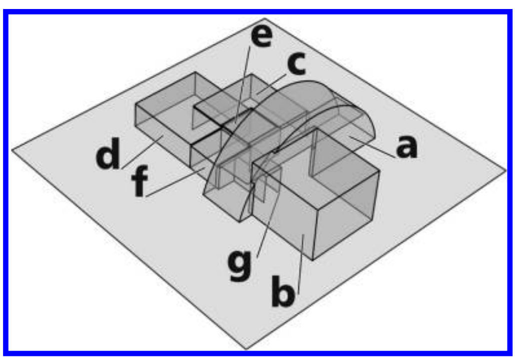

Figure 4. The initial designed form with labeled components.

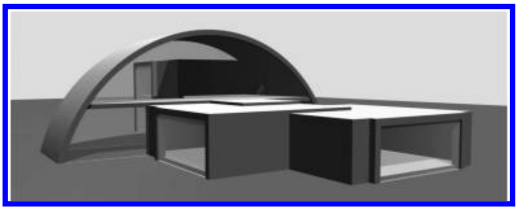

Figure 5. The view of the designed form.

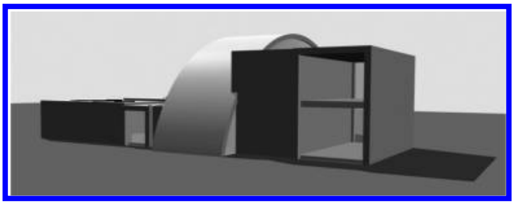

Figure 6. Another view of the designed form.

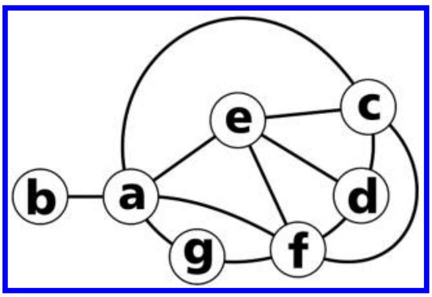

Figure 7. The simple graph for the form in Figure 4.

between components. In consequence the relational structure of the semantic of the first-order formulas, is simple graph shown in Figure 7. This graph can be a starting point of specifying other relations and functions.

During the design process when the design constraints force modifications on the form, there exists a possibility to transform the simple graph into an appropriate hyper-graph. The latter graph allows one to represent multi-argument relations.

6 CONCLUSIONS

This paper is the next step in developing graph-based data structures to support visual design. In the proposed approach the designer's modifications of drawings are reflected by operations performed on their graph representations. Then graphs are translated to formulas of the first-order logic, which describe design knowledge.

The presented prototype system *HGSDR* has been tested on functional-oriented designing floor-layouts. Succeeding tests will be concerned with form-oriented designing. The present implementation is written in such a way that a new application requires mainly changes in the editor module.

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Low carbon ontology development using information retrieval techniques

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ABSTRACT: The paper describes a methodology used to develop ontology for Low Carbon Domain, taking into account the wealth of existing semantic resources in the construction sector. The latter range from construction taxonomies to energy calculation tools and internal data structures (i.e. conceptual database schema). The paper argues that taxonomies provide an ideal backbone for any ontology project. Equally, textual documents have an important role in sharing and conveying knowledge and understanding. Therefore, a construction industry standard taxonomy (IFC) is used to provide the seeds of the ontology, enriched and expanded with additional concepts extracted from large construction sustainability and energy oriented document bases using information retrieval (tf-idf and Metric Clusters) techniques. The developed "SCrIPt (Sustainable Construction Service Platform)" ontology will be used as the semantic engine of the Sustainability Construction Portal, commissioned by the Welsh Assembly Government.

1 BACKGROUND

The UK is required to meet EU commitments relating to the reduction in energy to achieve an 80% cut in CO_2 emissions by 2050 and 20% of its total energy supply from renewable energy sources by 2020. Answering ways to achieve such energy transformation, the UK Chancellor of the Exchequer announced in the 2008 budget a zero carbon target for schools from 2016, Public sector buildings from 2018, and all other non-domestic buildings 2019. These announcements follow a 2007 announcement for zero carbon homes from 2016. Supporting these policy requirements, the UK building regulations will be amended in 2010 and 2013, with the target CO_2 reductions embedded. The Welsh Assembly Government's (WAG) aspiration for zero carbon for new buildings has pushed to initiate actions to meet the targets through improving sustainability knowledge availability (as reflected in the Sustainable Building Portal led by the Wales Low/Zero Carbon Hub), skills upgrading, training, education, availability of materials and adapted processes, and technology advances.

However, construction stakeholders involved in new or refurbishment projects are faced with: (a) complex legislation related to low carbon buildings, (b) a plethora of overlapping commercial tools supporting the process of delivering low carbon buildings, (c) numerous guidelines and documentation related to low carbon buildings, (d) an increasingly rigorous energy certification process, and (e) lack of clarity on types of financial assistance and eligibility criteria. Therefore, it is imperative to make building energy expertise widely available; in particular during the early design stages of a project, when most of the key decisions that impact on energy are made.

To address the questions raised above, an ontology development based project named ScrIPt (Sustainable Construction Service Platform) was recently started in Cardiff University in close collaboration with the Wales Low/Zero Carbon Hub, BRE Wales, and Constructing Excellence in Wales, and a large industry base representing stakeholders from the construction industry in Wales. The ScrIPt Low Carbon Domain ontology takes into account the wealth of existing semantic resources in the construction sector. A construction industry standard taxonomy (IFC) serves as the seeds of the ontology, enriched and expanded with additional concepts extracted from large construction sustainability and energy oriented document bases using information retrieval (tf-idf and Metric Clusters) techniques. The developed SCrIPt ontology will be used as the semantic engine of a Sustainability Construction Platform, commissioned by the Welsh Assembly Government.

2 EXISTING ONTOLOGY DEVELOPING METHODOLOGIES

As reported by (Cristani and Cuel, 2005), a variety of methodologies have been developed for dealing with ontologies. These include:

Methodologies for ontology building (Pinto and Martins, 2000; Haava, 2004); Methodologies for ontology reengineering (Klein, 2001); Methodologies for ontology learning (Kietz et al., 2000; Cimiano and Volker, 2005); Methodologies for ontology evaluation (Kalfoglou and Robertson, 1999; Gomez-Perez, 2001); Methodologies for ontology evolution (Klein et al., 2001; Stojanovic and Motik, 2002); and Methodologies for ontology merging (Klein, 2001; Euzenat, 2004).

The co-existence of numerous methodologies suggests that a consensual methodology is difficult to establish due either to the lack of maturity of the field or the difficulty of developing a methodology adaptable to different applications, sectors, and settings. For instance, most of these methods and methodologies do not consider the collaborative and distributed construction of ontologies.

Existing methodologies for building related ontologies can be distinguished by two main aspects:

a. The degree of dependency of the ontology on its application field (i.e., application dependent, semi-application dependent, or generic); and/or
b. The mechanism for deriving the ontology: generalization or specialization.

In relation to aspect (a), some methods use the application field as a starting point for building the ontology and are therefore application dependent. This is the case of the KACTUS project (Bernaras et al., 1996) and the On-To-Knowledge methodology (Staab et al., 2001). Other methodologies can be described as semiapplication dependent as they have the aspiration to be generic while using a given application as a reference. This is the case of the Gruninger and Fox methodology (Gruninger and Fox, 1995). Finally, some methodologies are generic, hence application-independent, since the ontology development process is totally independent of the uses of the ontology. This is the case of Uschold and King methods (Uschold and King, 1995), and Methodology (Fernandez-Lopez et al., 1999).

In terms of the mechanism to derive the ontology (aspect b), if we compare the KACTUS and the Sensus methods, in the former the ontology is built by means of an abstraction process from an initial knowledge base, while, in the latter, an ontology skeleton (presented in the form of a simple taxonomic structure) is automatically generated from a huge ontology developed by merging and extracting information from existing electronic resources, including the semantic database of WordNet and the English Dictionary.

The existing different ontology development methodologies are either generic, discipline/application specific only or are applied to a different domain using different techniques. The ScrIPt methodology takes full use of the established tf-idf and Metric Clusters techniques to identify relevant ontological concepts and their relationships to build up the entire low carbon ontology.

3 THE SERVICE ORIENTED SCRIPT SYSTEM FRAMEWORK

The proposed service oriented SCrIPt system framework is illustrated in Figure 1, which forms the reference for development of the platform. This architecture allows users of SCrIPt to use its services from within the "Sustainable Building Portal" developed by the Wales Low/Zero Carbon Hub, or from their preferred corporate knowledge system or portal, integrating them and allowing them to be used as both a source of knowledge and to support their existing collaborative processes.

ScrIPt uses a service-based approach, whereby the various services, including KM functionalities, would be packaged as discrete services, each accessible via the SCrIPt API and brokered by the 'SCrIPt Kernel'. This architecture is discussed briefly below.

Those 'SCrIPt Comprehensive Core Services' will be specified at the level of granularity that will allow maximum flexibility in use, while minimising the effort required to access specific functionality at an application level. The various service managers define the APIs for these services.

The Ontology service provides the functionality required to make the Low Carbon ontology available to the SCrIPt services, which may require it.

The visualisation service offers means for SCrIPt users to visualise low carbon resources, including documents, according to the type of device in use and their own display preferences.

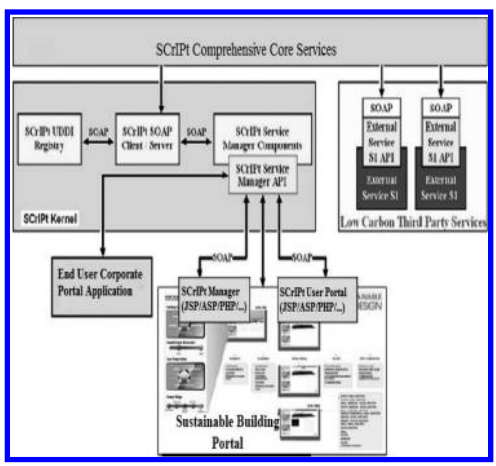

Figure 1. SCrIPt system framework.

The Maintenance Service provides means for enabling the SCrIPt system to maintain consistency amongst the documents and knowledge items indexed in the SCrIPt low carbon knowledge base as regulations get updated or new regulations released.

The Knowledge Indexer Service provides means to produce ontological full text indexing of each document managed by SCrIPt. The indexed version of the document is then used by the platform to perform possible initial searches or submit the document to produce an ontology based semantic representation.

The Extractor Service presents functions that enable SCrIPt to perform knowledge extraction tasks. The result of this extraction will be to make the knowledge item available for manipulation within the SCrIPt system via its ontological representation.

The Knowledge Searcher Service provides functionality enabling the user to perform searches across knowledge items or documents represented in the SCrIPt system, and to allow them to retrieve those knowledge items and their representations from the system.

The Knowledge Discoverer service provides functionality that will allow the user to search for useful documents and make them available to the system.

The Profiler Service is used to perform and manage user profiles to better direct user searches. The user would be required to register to SCrIPt, define his/her low carbon knowledge interests, and other related information. The system would then learn with a user's searches and interaction with SCrIPt and enrich his/her profile in a dynamic way.

The Dissemination Service is used to provide methods which enable the dissemination of low carbon knowledge and documents to other users of the system through a 'push' mechanism.

4 SCRIPT ONTOLOGY ARCHITECTURE

The ScrIPt ontology (Figure 2) is structured into a set of discrete, core and discipline-oriented, sub-ontologies referred to as modules.

The IFCs play a pivotal role in the representation and conceptualization of a building, however it cannot support in its present form, building thermal analysis and low carbon design. The IFCs need to be enhanced to support features (concepts, facets, and semantic relationships) required by existing energy calculation, simulation, and compliance checking tools while embedding the lifecycle dimension necessary to provide total life-cycle accounts of energy consumption and carbon emissions of a building design (Rezgui, Y. 2001). The IFCs need therefore to be promoted to a low carbon ontology by enriching and expanding with

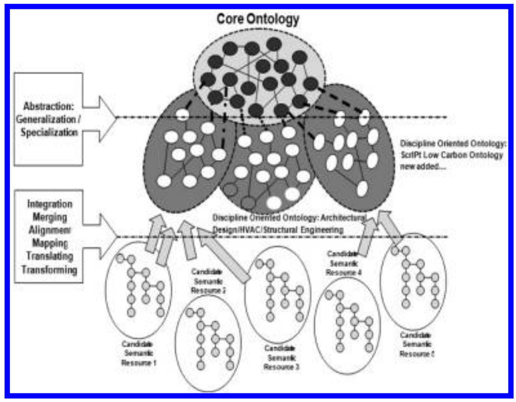

Figure 2. ScrIPt ontology architecture.

additional concepts and facets extracted from the gathered low carbon document repository and from the data structures that underpin industry energy calculation, simulation, and compliance checking tools. Given the requirements identified in the previous section, the

Each module features a high cohesion between its internal concepts while ensuring a high degree of interoperability between them. These are organized into a layered architecture with, at a high level of abstraction, the core ontology that holds a common conceptualization of the whole construction domain enabled by a set of inter-related generic core concepts forming the seeds of the ontology. These generic concepts enable interoperability between specialized discipline-oriented modules defined at a lower level of abstraction.

This middle layer of the architecture provides discipline-oriented conceptualizations of the construction domain. Concepts from these sub-ontologies are linked with the core concepts by generalization/specialization (commonly known as IS-A) relationships. The third and lowest level of the architecture (Figure 2) represents all semantic resources currently available, which constitute potential candidates for inclusion into ScrIPt either at the core or discipline level. These candidate ontologies are organized as follows:

Low Carbon Official Resources: this forms the overall low carbon publicly available information and knowledge. Low Carbon Proprietary Resources: this is company specific, and forms the intellectual capital of some leading SME and large construction firms. Low Carbon Practical Knowledge: this is knowledge acquired by individuals through practice drawing from the two above categories of knowledge. Commercial Low Carbon Knowledge: this knowledge is formalised and conceptualised by software vendors through their commercial offering.

The ScrIPt low carbon ontology populated from the concept stage of a building project, will evolve through the design, construction, and building maintenance stages, that will provide a true virtual and semantic representation of the building. Once the low carbon ontology is in place, an ontology-based semantic representation of all gathered low carbon documentation will be produced and will form the low carbon knowledge base.

5 SCRIPT ONTOLOGY DEVELOPMENT APPROACH

A particular approach was adopted in ScrIPt to build and expand the ontology. This involves selecting and making use of a large documentary corpus used in the discipline and ideally produced by the end-users (Rezgui, Y. 2006). Expanding or building ontology from index terms extracted from commonly used documents in a given discipline requires a few operations organized into steps. These are described below and are applied to each document of the selected documentary corpus.

5.1 *Document cleansing*

This step aims at reducing the document to a textual description that contains nouns and associations between nouns that carry most of the document semantics. This involves the following steps:

Lexical analysis of the text in order to deal with digits, hyphens, punctuation marks, and the case of letters; Elimination of stop words: this has the objective of filtering out non-content words, such as "the" and "of".

5.2 *Key word extraction*

This step aims at providing a logical view of a document through summarization via a set of semantically relevant key words. These are referred to, in this stage, as index terms. The purpose is to gradually move from a full text representation of the document to a higher-level representation. In order to reduce the complexity of the text, as well as the resulting computational costs, the index terms to be retained are all the nouns from the cleansed text. Several authors (Baeza-Yates and Ribeiro-Neto, 1999; Broglio et al., 1995) argue that nouns, as opposed to verbs, adjectives, and adverbs, carry out most of the semantics of a text document. This is assumed to be the case for the construction domain where technical documentation refers to noun-based terms, such as Products, construction materials, and resources. Concepts in the construction sector are sometime carried out by more than one term, such as "Curtain Wall" and can therefore be conveyed by bigrams. More generally, the notion of an n-gram can be found in the literature when a sequence of n terms is regarded as a single object. While n-grams play a key role in capturing term collocations (Tomovic et al., 2006), it is also worth noting that computation of n-gram probabilities does not accurately cater for rare term collocation events (Omelayenko, 2001). The approach presented here combines nouns co-occurring with a null syntactic distance (i.e. the number of words between the two nouns is null) into a single indexing component, regardless of their collocation frequency. These are referred to as noun groups (non-elementary index terms).

The result of this step is a set of elementary and non-elementary key words that are representative of the discipline being conceptualized.

5.3 *Integrating index terms into core and sub-ontology*

Two types of concept integration are possible (Omelayenko, 2001): concept level integration and syntactic level integration. Concept level integration requires inference over the domain ontology to make a decision about integration of a particular pair of concepts. Syntactical integration defines the rules in terms of class and attribute names to be integrated. Such integration rules are conceptually blind but are easy to implement and develop (Omelayenko, 2001). The approach used for concept level integration makes use of a pivotal semantic resource, ideally a thesaurus or taxonomy.

As highlighted in (Baeza-Yates and Ribeiro-Neto, 1999) a glossary or thesaurus can provide a controlled vocabulary for the extension of the ontology based on the identified key words. A controlled vocabulary presents the advantage of normalized terms, the reduction of noise, and the possibility of turning key words into concepts with clear semantic meaning.

For each identified key word, it is important to quantify the degree of importance (in terms of semantics) it has over not only the document but also the entire documentary corpus selected for the given discipline. The following formula, known as "Term frequency-inverse document frequency" (tf-idf) (Baeza-Yates and Ribeiro-Neto, 1999; Salton and Buckley, 1988), is used:

$$W_{i,j} = f_{i,j} \times idf_i \quad (1)$$

where $W_{i,j}$ represents the quantified weight that a term t_i has over the document d_j; $f_{i,j}$ represents the normalized occurrence of a term t_i in a document d_j, and is calculated using Equation (2):

$$f_{i,j} = \frac{freq_{i,j}}{\max_{\text{for all terms in document}} \text{freq}_{\text{term, j}}} \quad (2)$$

where $freq_{i,j}$ represents the number of times the term t_i is mentioned in document d_j; computes the maximum over all terms which are mentioned in the text of document d_j; idf_i represents the inverse of the frequency of a term t_i among the documents in the entire knowledge base, and is expressed as shown in Equation (3):

$$idf_i = \log \frac{N}{n_i} \quad (3)$$

where N is the total number of documents in the knowledge base, and n_i the number of documents in which the term t_i appears. The intuition behind the measure of $W_{i,j}$ is motivated by the fact that the best terms for inclusion in the ontology are those featured in certain individual documents, capable of distinguishing them from the remainder of the collection. This implies that the best terms should have high term frequencies but low overall collection frequencies. The term importance is therefore obtained by using the product of the term frequency and the inverse document frequency (Salton & Bukley, 1988).

The following hypotheses apply when comparing concepts from the ontology with extracted key words from the documents:

If an ontological concept and a document key word have the same name or a common stem then they can be considered as semantically equivalent. This is motivated by the nature of the low carbon jargon where variations of the same noun are used in various contextual situations.

If an ontological concept and a document key word have distinct names, both concepts are looked up in the existing semantic glossary. The algorithm checks first if both concepts are related through a specialization/generalization mechanism. In the affirmative, the key word is added as such to the ontology in accordance with the identified relationship, and is marked as "new", which means that it will only be made officially part of the ontology once approved by the relevant knowledge expert(s). If the ontological concept and the document key word are not related through a specialization/generalization relationship, then the quantified semantic weight of the index term (Equation 1) is used as a criterion to decide whether it should be added as a concept to the ontology. At this stage, only index terms with a relatively high semantic weight were retained and added to the ontology with no relationship to other concepts defined at this stage. Finally, the properties of the new ontological concepts are either refined or defined for new concepts that have been integrated into the ontology. This task is undertaken manually by the knowledge experts.

5.4 *Ontology concept relationship building*

The next step in the methodology includes building the relationships connecting the concepts, including those that have not been retained in the previous stage. Concept relationships can be induced by patterns of co-occurrence within documents. As described in (Baeza-Yates and Ribeiro-Neto, 1999), overall relationships are usually of a hierarchical nature and most often involve associations between "broader" and "narrower" related terms. Broader term and narrower term relationships define a specialization hierarchy where the broader term is associated with a class and its related narrower terms are associated with specialized instances of the class. While broader and narrower terms relationships can be defined automatically, dealing with related term relationships is much harder. One reason for this is that these relationships depend on the specific context and the particular needs of the group of users, and are thus difficult to establish without the knowledge provided by specialists. Three different main types of relationships are listed below:

Generalization/Specialisation Relationship
Composition/Aggregation Relationship
Semantic relationship between concepts

The last two categories above are addressed in this step. The process is semi-automated in that relations are first identified automatically. Contributions from knowledge specialists are then requested to qualify and define the identified relations. In order to assess the relevance of relationships between concepts, an approach that factors the number of co-occurrences of concepts with their proximity in the text is adopted. This is known as the "Metric Clusters" method (Baeza-Yates and Ribeiro-Neto, 1999) (Equation 4). This proceeds by factoring the distance between two terms in the computation of their correlation factor. The assumption being that terms which occur in the same sentence, seem more correlated than terms that appear far away.

$$C_{u,v} = \sum_{t_i \in V(S_u)} \sum_{t_j \in V(S_v)} \frac{1}{r(t_i, t_j)} \quad (4)$$

The distance $r(t_i, t_j)$ between two key words t_i and t_j is given by the number of words between them in the same document. $V(S_u)$ and $V(S_v)$ represent the sets of keywords which have S_u and S_v as their respective stems. In order to simplify the correlation factor given in Equation 4, it was decided not to take into account the different syntactic variations of concepts within the text, and instead use Equation 5, where $r(t_u, t_v)$ represents the minimum distance (in terms of the number of separating words) between concepts t_u and t_v in any single document.

$$C_{u,v} = \frac{1}{\mathrm{Min}[r(t_u, t_v)]} \quad (5)$$

The following exception should be noted: in the case where the minimum distance between two terms is null the correlation factor will return "∞". When this exception arises, the correlated terms are considered as candidates to form a composite term. The assumption taken in the computation of Equation 4 is that the closer the correlation factor is to 1, the stronger the correlation between the two terms is likely to be. Based on the correlation factors, index terms are linked to relevant concepts from the ontology with a blind relationship. In order to establish a threshold for the correlation factor, it is suggested that only terms co-occurring within the same sentence should be considered.

The domain knowledge experts have the responsibility of validating the newly integrated index terms as well as their given names, and then defining all the concept associations that do not belong to the Generalization/Specialization category. First, these relationships will be established at a high level within the Core Ontology, and then subsequent efforts will establish relationships at lower levels within the discipline ontologies.

A wide range of documents will be selected for the low carbon ontology development, including Full Specification Documents, related technical regulations, Bills of quantity, and internal company technical documents. Given the project-oriented nature of the industry, these were selected across several projects so as to maximize the chances of including a broad range of the relevant concepts and terminologies used.

6 CONCLUSION

The ontology developed to date is far from being complete, and will probably never be, as an ontology should be viewed as a living system. Similar efforts, such as the ISO STEP project and its application to various industry sectors (including manufacturing), have taken almost a decade or longer to come to fruition (Rezgui, Y, Zarli, A, 2006). The ScrIPt ontology is by no means different. The issue of the existence of a unique ontology for an entire sector remains open.

The ScrIPt project is currently in its early stage, the ontology development is ongoing, and the detailed case studies will be executed to further evaluate the framework. While the ScrIPt Core Ontology forms a robust basis for interoperability across the discipline-oriented ontologies, the latter will need adaptation and refining when deployed into an organization and used on projects.

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Process-mediated planning in A/E/C through structured dialogues

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ABSTRACT: Project planning in the Architecture, Engineering and Construction (AEC) industry relies heavily on individual skills, experience and improvisation. In an attempt to increase predictability and efficiency, and to improve knowledge retention across projects, this paper proposes a more systematic approach to project planning. It does so by introducing the notion of a meta-process model that embodies and cultivates the logic and intelligence of incremental and collaborative planning activities in a given domain. Planning tasks are encoded and enacted/enforced as a set of processes that drive structured dialogues between project partners. To make this possible, a system architecture for meta process modelling and execution is introduced. The concept of the chosen approach can be classified as process mediation through structured dialogues. It is applied to the planning of Design-Build project delivery between an owner, architect and other parties.

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1 INTRODUCTION

Project planning in the Architecture, Engineering and Construction (AEC) industry requires much experience from individual planners. Existing planning software tools typically provide features to organize design and construction activities, to optimize resource allocations, to visualize expected project schedules, to coordinate project execution, and so forth. Figure 1 shows a typical user interface of these tools, in this case Primavera. In order to arrive at a comprehensive project plan, tool users must possess project and domain specific know-how, along with anticipation and improvisation skills that are not provided or supported explicitly by the planning environment. Even the user's complete familiarity with the software functionality provides no guarantee for the quality of a generated project plan, and whether its content is consensus based, reliable and comprehensive. Moreover, most planning tools are not collaborative in the sense that they do not specify who is responsible for generating what planning data, and when. Instead it is often a single project manager who assimilates the project plan. A lot of embedded planning knowledge is thus unscripted, undocumented and preserved only in personal memories or in scattered documents, making its transfer and enrichment over time limited. This paper introduces research that would empower project partners to systematically and transparently work towards a solid project plan by enactment of a planning workflow, expanded by so-called "structured dialogues".

The combination of workflows with structured dialog not only assigns consecutive tasks according to a predefined logic, but it is designed to also support the cooperative nature of planning activities by "ushering" project partners when needed into (virtual) meetings. This combination is an attempt to structure the interaction and make the collaborative planning productive and efficient.

The validity of this approach rests on the premise that a planning process and its implicit knowledge can be modeled as task logic, where the more collaborative aspects of the planning process

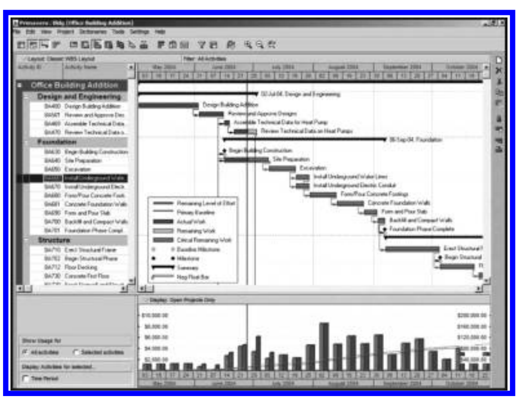

Figure 1. Screenshot of a typical project planning tool.

can be expressed in structured dialogue extensions of the task logic. It is expected that the execution of such a dialogue-enabled workflow would indeed add value to existing planning practices. It is the intention of the research to verify our expectation with project planners in practice.

2 TOWARDS BETTER PROJECT PLANNING

2.1 *State of the art*

Project planning can be defined in general as the projection of the realization or achievement of a plan (Webster). More precisely, project planning within project management can be defined as the process to quantify the amount of time and budget it will cost to undertake a temporary endeavor to create a unique product, service or result. The purpose of project planning is creating a project plan that a project manager can use to track the progress of his team (Wikipedia). A carefully planned and organized strategy is needed to accomplish the specified objectives. The strategy includes developing a plan which will outline the goals, explicitly set the tasks to be completed, determine how they will be accomplished, estimate time and resources (both human and material) needed for their completion. How projects are planned and managed will seriously impact the profitability of the ventures that they are intended for and the quality of the products or services they generate. The US-based Project Management Institute (PMI 2000a) defines project planning as the development and maintenance of formal, approved documents used to guide both project execution and project control. The primary uses of the project plan are to document planning assumptions and decisions, facilitate communication among stakeholders, and document approved scope, cost, and schedule baselines. A project plan may be anywhere between a high-level summary or a detailed work plan. A couple of well known techniques are typically used for the purpose of planning and scheduling the tasks in project management: Work Breakdown Structures (WBS), Gantt charts, the Critical Path Analysis (CPA) and the Program Evaluation and Review Technique (PERT). A WBS is a list of tasks ordered as a tree of activities that take into account their lengths and contingencies. Gantt charts arrange the different events in synchronism and associate each task with its owner and its estimated beginning and ending time. The CPA focuses on the timing by more explicitly taking into account the interdependence of critical tasks. It identifies the tasks that need to be completed on time to meet the intended project deadline (the critical path), while considering the possibility of parallel tasks, and wait and slack times for every activity. The Program Evaluation and Review Technique (PERT) is a variation of the CPA in that it follows a probabilistic rather than a deterministic approach, taking into account the likelihood of activity durations.

Project planning applications typically tend to be measured by their ability to support the intricacies of the traditional diagramming techniques listed above, while basically ignoring that they only reflect the final outcome of a long and disordered planning process that still depends heavily on the vast and largely undocumented knowledge, improvisation skills and assumed experience of individual planners. The systematic build up of meaningful and comprehensive planning data is not supported.

Current project planning applications tend to emphasize the efficient visualization of time schedules with optimised resource allocation, rather than focusing on the methods and process of arriving at a comprehensive project plan that addresses all potential issues. Current planning practices incorporate little systematic effort to capture and reuse the implicit domain knowledge of experienced project planners as they make preparatory decisions. The lack of stored procedural information leads to a rather ad-hoc approach to project planning, an enduring over-dependence on individual experience, and constant reinvention of the wheel for every new construction project.

Existing collaborative virtual environments (CVE) mainly strive to accomplish a more effective communication between project planners, with any-time/any-place access to planning data. Where actual processes are supported, they typically involve low-level, rigid and execution-phase oriented workflows, such as the aggregation of some Change Requests from the Contractor into an eventual approved Change Order from the Owner. The project planners themselves usually have little or no direct control over the modelling, customization or adjusting of any offered workflows, if provided at all. Consequently, current Web-facilitated planning services fall short in cultivating essential process embedded knowledge; at best providing means but no roadmap to arrive at a comprehensive project plan.

2.2 *A way forward*

Few professionals in the design and construction industry will dispute that better project planning will lead to better project deliverables in terms of time, cost and quality. An enhanced preparation ahead of time can reduce the amount of change orders, misunderstandings, budget overruns, litigation and delays later on during project execution. Yates & Hardcastle (2003) describe two case studies from the Hong Kong construction industry where large numbers of claims due to—among others—contractual incompleteness, and consequent ex post adjustments, result in significant cost increases for the owners. The authors state that if participants in the construction process—especially the client—would have a better understanding of the factors that cause conflicts and disputes, they could take appropriate avoidance measures.

It should be noted that contractual incompleteness or contractual ambiguity is one of the leading causes of disputes. The 'Dispute Avoidance and Resolution Task Force' of the American Arbitration Association comments in its February 1994 newsletter (AAA 1994): "During the past 50 years much of the United States construction environment has been degraded from one of a positive relationship between all members of the project team to a contest consumed in fault finding and defensiveness which results in litigation. The industry has become extremely adversarial and we are paying the price … A positive alliance of the parties (involved in the construction process) constitutes an indispensable link to a successful project." New types of partnerships and alliancing contracts could reduce the litigious climate in construction projects and create a more synergetic atmosphere, but in order to improve the situation adequate vehicles are needed for empowering partnerships to engage in better project planning.

Recent research in Canada and the United States indicates that the general traditional practice of shifting project risks to the other contracting party by using disclaimer clauses in contracts, is a significant reason for parties to increase the total cost of a project (Zaghloul & Hartman 2003), with assessed premiums between 8 and 20%. Any improvement in the process and more appropriate risk allocation would deliver substantial savings for the construction industry. Research also shows that there is an important relationship between trust and risk allocation through contract provisions. According to Zaghloul & Hartman (2003) the five most commonly used exculpatory clauses in construction contracts regard (1) uncertainty of work conditions, (2) delaying events, (3) indemnification, (4) liquidated damages, and (5) sufficiency of contract documents. Based on a survey among industry experts—owners, consultants and contractors—with more than 300 respondents, it can be concluded that a trust relationship between the contracting parties should exist first to reach a better risk allocation process.

Certain stages are proposed to achieve higher pre-project trust:

- A clear understanding of risks being born by each party and who owns and manages that risk;
- More time and effort in the front-end of a project and sufficient experience to manage or mitigate the risk and administrate the contract;
- Adequate risk-sharing or risk-reward systems to share the benefits if the risk does not occur during the project lifecycle; and
- A negotiation phase prior to the start of the contract, required to build a trust relationship between the contracting parties; this negotiation phase can be part of the contract itself.

This paper gives an account of the research that led to a prototype planning system that addresses many of these points.

3 A NEW APPROACH

The first step in our approach is to develop a meta-level process model of planning activities. A useful framework is provided by the Project Management Body Of Knowledge (PMI, 2000a; 2000b). The PMBOK defines an ordered abstract set of planning sub-processes that are interconnected by required inputs and outputs. For the purpose of our research, the PMBOK framework also has some shortcomings however, in that it is not AEC-specific, its intermediary deliverables and process timing have not been stated in detail, and it is not collaborative in the sense that it does not specify between construction project partners who should do what and when. In order to mitigate these shortcomings, a smaller slice within the larger planning framework was selected that could be worked out into a detailed, collaborative and AEC-specific example case.

In our perspective on planning activities, the formal capture of all tasks and their interdependencies leads to a so-called Project Planning Process Model (PPPM) which sits at the top of the project collaboration pyramid (Fig. 2).

The figure conveys that collaboration between project partners takes place at the strategic, tactical

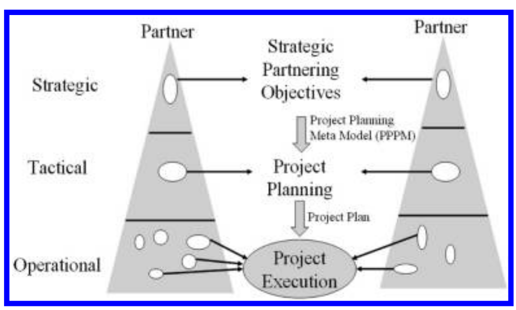

Figure 2. Strategic, tactical and operational project planning.

and operational level. Figure 2 positions project planning at the tactical middle layer between strategic partnering objectives and actual project execution. Strategic objectives are expressed as the business rules that govern how an enterprise wants to engage in a partnering dialogue. The rules are typically the result of strategic management decisions. They paint the broad brush strokes of the Project Planning Process Model (PPPM) which is consequently refined to show all the tactical negotiation steps and the dialogue templates that each step is linked to. The resulting PPPM governs the tactical project planning process, typically conducted by experienced project planners from all potential partners. The tactical process leads to a project plan which should be complete enough to guarantee the successful management of the actual project execution, conducted by designers, engineers and project managers from all parties. In Figure 2, a project plan is incrementally generated by applying a meta-process that is defined at the strategic level. Such a meta-process consists of workflows that are augmented with support for structured dialogues. The process flow convenes the appropriate people around tasks and sets up the agenda and topics of their task meetings, while the structured dialogs offer the detailed information items that need discussion and agreement to successfully complete their tasks and move on.

The enactment of the PPPM in a workflow engine lets groups of project planners—e.g. companies or project teams—enact workflows in which the system prompts participants for each activity to access, submit or edit deliverables that were generated upstream or that are needed downstream. This is accompanied by data templates that are incrementally populated as new tasks are launched and executed. The outcome forms a comprehensive project plan that addresses issues like risks, rewards, responsibilities, arbitration, deadlines and quality assurance. This (tactical) project plan will now be used to manage the execution of the project. In this paper we only deal with the planning stage which has the project plan as its final outcome.

It is important to note that the PPPM is not meant to impose a form of "process tyranny" on the project planners. Instead, participants may opt to start or abort any tactical workflow (represented in the PPPM) at any time, depending on the need to enter into improvisation or abort because of perceived lack of support from the system at a given instance. The process-mediation is intended to avoid information overload for participants at all times, presenting them only with the information needed at a certain point of the planning—as opposed to the overwhelming amount of random data that may be present in an unstructured planning trajectory. In general, process guidance can increase predictability and knowledge retention across projects, thus positively influencing quality and productivity.

The meta-process will guarantee both the timeliness of invoking planning events and the comprehensiveness of the planning outcome, by reducing the chance for errors and omissions. Also, it will avoid an ad-hoc approach to contract definition, and instead foster knowledge retention in recurring partnering processes (Allee 1997, Kamara et al. 2002). And finally, joint project planning through a mediated process will increase transparency and mutual understanding of project expectations among the parties involved.

4 DEVELOPMENT CONCEPT

4.1 *Workflow modelling*

Workflow modelling is defined as the computerized facilitation or automation of a business process (WfMC 1999a). By applying workflow management, documents, information or tasks are passed from one participant to another in a way that is governed by rules or procedures. The workflows that form the PPPM should be expressed in a common, standardized workflow modelling representation, so as to allow both creation and execution in a broad variety of adhering software packages.

Figure 3 shows a customized process modeler with which PP workflows can be generated in a standardized format (XPDL), while a suitable workflow engine enables the launching and enactment of instances of a PP workflow. The process model contains horizontal bars ("swim lanes") assigned to roles (e.g. in a construction project these might be the owner, architect, or contractor), where each role can be played by an individual or group (company or organization). The various

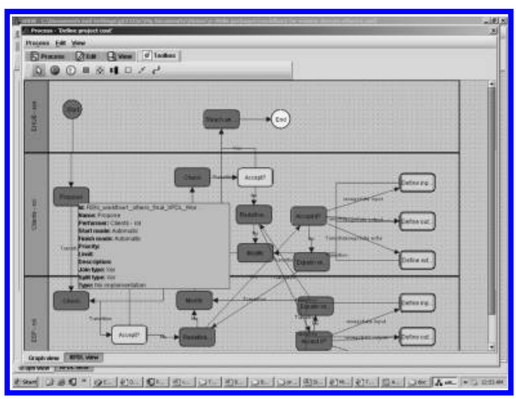

Figure 3. Customized workflow modelling module.

activities in the process model (represented by boxes in the horizontal bars) are linked to files in the document management module of the CVE platform.

A variety of different tools may be used to analyze, model, describe and document a business process. In order to provide a common method to access and describe workflow definitions, the Workflow Process Definition Language (WPDL) has been established (WfMC 1999a; 1999b). The WPDL also has a version specifically aimed at Internet applications: XPDL (WfMC 2002). Our research has adopted the use of XPDL and uses the open source JaWE workflow modeler.

4.2 *System concept*

Generating the fully functional system would require the following steps:

1. Expand an existing workflow taxonomy (XPDI) to include syntax for structured dialogues
2. Develop a high-end process modeler customized to include that syntax
3. Develop a corresponding full-featured Collaborative Virtual Environment (CVE)
4. Model an example planning process in detail (e.g. Design-Build project delivery)
5. Extensively test and measure the implementation with performance metrics
6. Validate the concept of the proposed solution (separating ends and means).

In the current phase of the research it was decided to add functionality on top of an existing e-HUBS platform, a CVE that allows the execution of standardized workflow models (Augenbroe, 2004). The workflows are linked to predefined data templates where items of concern, decisions, rationales, parameters, and documents (as described in Watson et al. 2002) are accessed (read) and/or submitted (write). These information items, together with the pre-defined process logic, guide the partners through the planning process, which is driven by the detailed workflows defined in the PPPM. Figure 4 shows the flow of activities in the envisioned project planning system. Planners do their work by enacting the PPPM workflows. When all workflows have been completed, the data templates will have been filled with information items that together form the complete project plan, containing the results of all activities and dialogues.

This repository should contain information with respect to all relevant issues such as risks, responsibilities, roles, rewards, arbitration, quality control, deadlines, deliverables, and so on. In this context, a role can be defined as a function that a human actor undertakes within a project. Filters can be

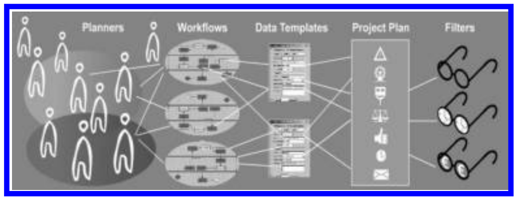

Figure 4. Conceptual system architecture.

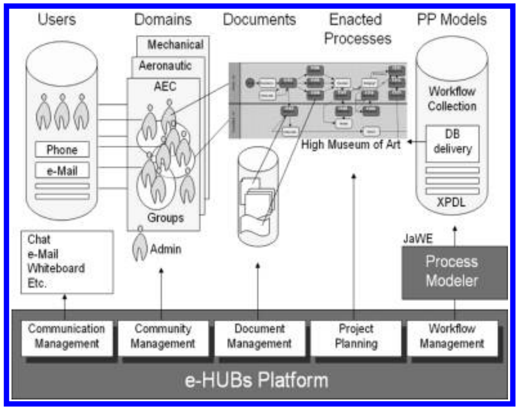

Figure 5. Major functional components.

defined to process the information in the planning data repository for downstream use. These filters can be set up to separate final outcomes from the intermediary deliverables (the project's audit trail) that led up to those results. For example, they could be used to generate specific documents, such as the project's overall financial data or task schedule.

5 IMPLEMENTATION

Figure 5 illustrates the overall configuration of the prototype system for process-mediated project planning. It is shown how the case of Design-Build (DB) project delivery would be supported by a embedded PPPM for Design Build in the PP model database. A project manager would select the model and launch an instance of the DB planning model and launch it in the workflow runtime engine for the selected project, the "High Museum of Art". In doing so selection of project partners, timeline and other will be done. Once the workflow is launched, all allocated project planners will be notified that are part of a project planning workflow. A separate module for structured dialogue support would be launched to structure joint activities by a running process.

As stated above, the prototype is built on the substrate of the e-HUBs platform, an existing CVE that contains not only all the typical functionality like community and document management, but also the special two modules of workflow management and project planning.

Although the process modeler in the e-HUBS platform does not explicitly support the concept of structured dialogues, their added value is demonstrated through a separate rapid prototype developed in MS Access. Though not truly integrated with the selected CVE, the prototype dialogue application, combined with the used skeleton functionality of the e-HUBs platform, can be envisioned to provide an initial prototype, serving as test implementation and proof of concept.

6 DESIGN-BUILD APPLICATION

The Design-Build process can be subdivided in the following main phases (Beard et. al. 2001):

A. Formation of the Owner's team and the Design-Build team (if non-permanent)
B. Selection of the most advantageous type of DB variant
C. Identification of facility needs (program definition)
D. Generation of preliminary design intentions (optional; if bridging is applied)
E. Pre-selection of qualified offerers (optional; if multiple competitors)
F. Proposal development and modification
G. Proposal negotiation and selection
H. Construction preparation.

The process starts after the selection of Design-Build or Bridging as the preferred delivery method for a project, and it ends with the resulting construction commissioning. The latter is usually considered to commence with the official signing of the so-called Part 2 agreement, which governs the detailing and realization of the facility proposed under the Part 1 agreement. The Owner must first define the initial scope statement, which provides a documented basis for making future project decisions and for confirming or developing common understanding of project scope among the stakeholders. As the project progresses, the scope statement may need to be revised or refined to reflect approved changes to the scope of the project. The scope statement typically includes a project justification (business need), a brief summary of the intended end-product (the building), intermediary deliverables (design and construction milestones), and project objectives (quantifiable criteria to measure success, such as cost and quality). All of the above is translated into a workflow similar to Figure 3.

Table 1 presents a snapshot of the catalog of activities for the DB/Bridging process, with the WBS phase they belong to (referring to a workflow package in the modeler) and with their initial resource allocation at the abstract level of roles. Each activity has been given a randomly assigned, progressive four-digit numerical key that is unique within the package for later identification purposes.

Table 1. Catalogue of DB activities (snapshot).

ID	Activity	WBS	Role
1102	Hire consulting Architect/Criteria consultant?	A	Owner
1103	Advise owner	A	Cons
1104	Determine ownership situation	B	Owner
1105	Apply fast-tracking?	B	Owner
1106	Apply bridging?	B	Owner
1107	Specify performance requirements	C	Owner
1108	Gather facility requirements	C	Cons
1109	Prepare bridging documents	D	Cons
1110	Approve design intent	C	Owner
Etc	Etc	Etc	Etc

The temporal task dependencies between the activities from Table 1 can be compiled in an overall process map, with arrows delineating the Activity Sequencing, and swim lanes for the five roles involved: Owner, Consultant (or "Owner's Architect"), Design-Builder, Architect-of-Record, and General Contractor. For more details, see (Verheij, 2005).

As indicated, the data output of one activity can be the input of the next, thereby connecting activities in a logical web of interdependencies. The WRD thus form an invisible but crucial data layer beneath the process diagrams.. Effectively the WRD constitute a second type of task dependencies beyond temporal connections between activities. These dependencies link activities by the fact that both activities have a link to the same data item in the WRD.

7 DIALOGUE SUPPORT

As mentioned earlier, currently the dialogue module is not integrated in the overall system architecture of the implemented prototype configuration. However, it is not hard to envision the possible seamless connections between these components, since the structure of the dialogue syntax extension builds directly on the existing fundaments of the standard workflow taxonomy.

Describing a use scenario for the proposed dialogue support system is based on the assumption that "Task Manager" and "Team Organizer" are actually integrated components. This assumption means that the process modeler (JaWE) would be able to also model dialogues and append them to activities ("JaWE+"), and that the Web-based workflow engine would be able to parse such dialogue extensions when enacting a process. Whereas the current dialogue support prototype is a separate client-server application, it would ideally be a fully integrated part of the configuration as illustrated in Figure 6.

With this system architecture, registered CVE users can model new or adapt existing processes, including structured dialogues—and then upload these dialogue-enhanced workflows into the project planning module of the platform for execution. Upon the launching of a process instance by a user, the embedded workflow engine starts dispatching tasks according to the logic defined in the uploaded process model. Users will find consecutive tasks on their to-do list, which they can access by clicking on them.

By clicking on a received task, a pop-up window appears with a data template that contains links (e.g. to a task-instruction Web site) and data fields, with previous submittals or needed deliverables (activity inputs and outputs; WRD). However, when an activity includes a predefined dialogue (of which the user is an Initiator), an extra link could appear which launches the dialogue support application. This dialogue support window lists fellow dialogue Initiators with contact information, it suggests which other dialogue participants to invite, proposes topics to address, and provides an environment to structure the interaction before, during and after the discussion—through respectively useful resources, space for propositions, and explicitly recorded decisions. This environment is intended to limit the dialogue's expansive solution space while focusing the participants on an efficient handling of their agenda.

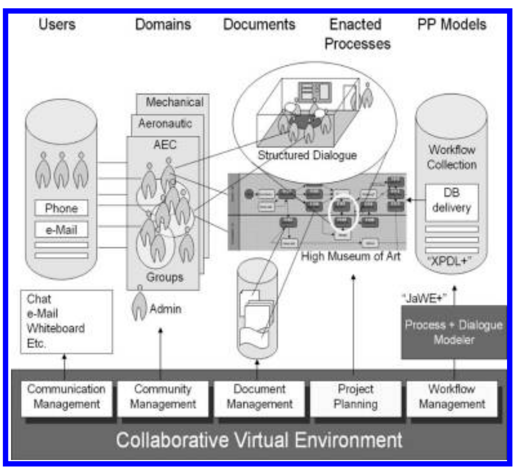

Figure 6. System with integrated dialogue module.

With the dialogue window open, the Initiator can use his own judgment to decide what type of dialogue he will propose, depending on the needed exchange of ideas, the size of the group, topics at hand, the setting, people's location, work culture, time pressure, etc. For example, he may decide to set up a formal synchronous meeting, by inviting participants to a future gathering. But he may equally well launch a conference call right away to get a simple dialogue out of the way immediately. The dialogue Initiators may opt to send the invitees a secure link to the online dialogue support window ahead of time, so that they too can prepare themselves in advance (view the agenda, access resources, suggest discussion topics, etc). Extended contact info can be solicited through a standard Web form by the dialogue Initiators upon electronic invitation to participate.

In Verheij (2005) it is shown how planning narratives are derived from a detailed process planning scenario, which contains a chronological storyboard with actual communication. This narrative of a structured dialogue should be seen against the backdrop of its "conventional" counterpart, which consists of a typical dialogue from a "day-out-of-the-life of a project planner" as it would occur now in a non-structured situation. The comparison is meant to make the argument, and provide anecdotal proof, that dialogue structuring supports and makes a contribution to actual project planning activities. Better organizing discussions can improve knowledge proliferation, decrease dependency on few experienced people, and prevent or at least reduce typical interaction problems, such as misunderstandings, inefficiencies, delays, errors, forgotten issues, rework and process breakdowns.

8 CONCLUSIONS AND FUTURE RESEARCH

The reported research aims to make project planning in the Architecture, Engineering and Construction (AEC) industry less dependent on individual skills, experience and improvisation. It does so by introducing a meta-process model that captures the logic of project planning in a given domain and from the perspective of a particular client organization. The meta-process model consists of a set of workflows that are linked to project information templates. Enacting this model enforces a more systematic approach to the planning of actual projects. The meta-process drives the interactive planning activities in and across organizations. As a demo, the approach is applied to the domain of Design-Build project delivery, for which a detailed workflow model was developed.

Project planning is a dynamic, inter-organizational and collaborative process which does not lend itself to the notion of a purely mechanistic task execution. In this research a hybrid approach is developed which mixes high-level task logic and information templates with the execution of structured dialogues between planners. Whereas a conventional workflow can be viewed as a "Task Manager", a structured dialogue can be regarded to include a "Team Organizer". For that to be possible, a dialogue taxonomy extension to existing workflow modelling technology is proposed based on a literature review and analysis of dialogue theories (Verheij, 2005).

The main contributions of this work are a new approach to computer-mediated process-driven project planning, a detailed workflow model of Design-Build project delivery, and a WF modelling extension to support the capture and management of structured dialogues.

To demonstrate the system it was applied to the Design Build planning process. The structured dialogue extension was demonstrated through a separate dialogue management prototype developed as a MS Access database module. The applied system configuration, though operational and useful for demonstration purposes, is still a prototype in its early stages of development, thus inhibiting extensive field testing yet. However, initial evaluations of the system's overall idea by industry practitioners and domain experts have provided a preliminary proof of concept in support of the hypothesis that project planning will benefit from process mediated structured dialogues.

Future research will target the following issues:

Dialogue Integration: An integrated environment is necessary with both a process modeler and an associated enactment environment able to handle structured dialogues attached to workflow activities.

Knowledge Retention: The mechanism to make processes and dialogues evolve and enrich themselves over time, beyond project and company borders, requires implementation of data exchange between individual project participants and the professional community at large (e.g. best practices, resources, etc).

Enhanced Workflow Modelling Capabilities: Currently available workflow modelling standards only provide a rudimentary set of basic interoperable modelling entities. Important features that could be supported are for example the collaborative definition of processes, and run-time process adaptation i.e. exception handling and/or permanent process design changes. For example, a running process may require the dynamic addition of an additional "swimlane" (actor) at some point. The workflow technology must allow such flexibility, without any running process instances collapsing.

Concept Scalability: Ideally, practitioners would gradually compose a library of processes or detailed sub-processes within larger more general processes. A classification of deliverables could cover typical industrial concepts like Change Orders, Requests For Information, and punchlists. The taxonomy of dialogue entities (topics, resources, etc.) and Workflow Relevant Data (deliverables) would thus have to be mapped on industrial concepts so as to categorize them adequately. That way, a project partner could for example easily look up all Change Orders on the project irrespective of the processes in which they were generated and whether he was involved in those processes or not.

Systematic Process Generation: Many system users may not be accustomed to modelling processes by nature, habit and education, since their core expertise will likely be a construction related trade. To benefit from the proposed process mediation, a systematic approach to defining workflows may have to be provided, such as one along the steps suggested in the PMBOK.

Quantitative Testing: End-user observations, case studies and surveys on further developed system versions will have to verify whether efficiency gains and improved knowledge management indeed occur.

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Information requirements of a generalized framework for jobsite decision making: Elicitation through scenario development

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ABSTRACT: The intelligent jobsite (IJS) presents a vision of a fully wired and sensed construction site. Researchers and commercial developers are developing specific applications and underlying sensing technologies. However, a realized vision of an IJS will involve re-use and re-purposing of shared data from multiple sources to support a wide array of decision support applications. There needs to be a generalized view of information in the environment which will allow re-use; such a view must be determined by usage scenarios to allow development of both data and higher level decision support constructs. This paper outlines a series of scenarios based on actual and projected applications for the intelligent jobsite, and presents key findings for generalized data types and decision support constructs.

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1 INTRODUCTION

The construction industry has been gaining increasing complexity for many reasons, including complex projects and more data which is collected in the built environment. The latter can enable more elaborate analysis and decision support for Engineers, but also increases complexity in the sense that there are many new sources of information (e.g. sensors, RFID) which collect a large amount of data that needs to be processed and interpreted to actually add value to processes (Edward and Tarek 2003; Jongchul et al. 2007; Song et al. 2005). Researchers have been working to develop specific applications to use data collected from a variety of devices for decision support in a differentareas (e.g. quality control, structural health monitoring, materials management, safety management). However, some data and devices are shared and used across these developed applications. It would be helpful to understand the relations among these devices and data collected from them and consider reusing and repurposing the common data across a wide range of applications. To address the reusability of data and devices during the decision support application development, a three-layer architecturewas proposed for decision making application development in ad hoc sensor network (O'Brien et al. 2009). The three layers include decision support layer, data processing layer and physical communication layer. In decision support layer, decision making application can be divided into several small decision chunks, each of which aims to fulfill a smaller task in the complete decision making process. The architecture has proposed a concept of multi domain application development. To make the architecture more practical and easy to implement, our research focuses on establishing a generalizable framework for cross-domain decision support application development on construction jobsites with imperfect data, which is common in practice. This research first analyzes the information requirements (including data collection devices) and decision making processes based on various decision making scenarios, and extracts the commonalities among them. Based on the analysis of common information requirements and decision rules, this research establishes a generalizable framework to support the development of cross-domain decision support applications. The second phase of the research will focus on the quality of data from different sources in different application domains and its impact on decision. Several techniques to support decision making with imperfect data are investigated in the research, and corresponding suggestions are made in this study. This paper presents an initial set of results of the information requirement extraction process to support the development of multi-domain decision making applications. The organization of the rest of this paper is as follows. In section 2, we reviewed the decision making problems on construction jobsite and information requirements for jobsite management. In section 3, we proposed taxonomy of decision making on construction jobsites. A proposed structured repository of required information for decision making is illustrated in section 4, and section 5 describes the procedure of using the repository to identify required information during scenario development. In addition, section 6 uses a crane operation safety scenario to demonstrate the information requirement extraction process and the potential use of identified information requirements. Finally, section 7 summarizes the results of the paper and proposes some directions for future research.

2 LITERATURE REVIEW

The construction industry has used wireless sensors and computing devices for decision making practice on jobsites in various different areas, including quality control (Giuseppe 2008), structuralhealth monitoring (Chintalapudi et al. 2006; Jeongyeup et al. 2005; Li and Liu 2007; Ning et al. 2004), materials management (Edward and Tarek 2003; Jongchul et al. 2007; Song et al. 2005), and safety management. Besides construction practice, researchers keep putting efforts to implement the concept of IJS to provide better decision making support in different areas (Navon 2009). Many current researches are prototypes and have not yet been adopted by industry. To facilitate the development and validation of these researches focusing on construction automation, National Institute of Science and Technology (NIST) establishes an intelligent and automated construction job site testbed to replicate the actual environment on real construction jobsite, and allows the participating researcher to test their prototype in the testbed (Lytle 2009). Through a workshop with participants from industry, academy and other areas in 2008, NIST identified the initial information requirements for material management, personnel management, equipment management, site management and operation management on jobsite (Lytle 2009). Although NIST has indentified some information requirements, the requirements are incomplete, especially for operations management (including safety and quality management). What's more, the NIST's study focuses on using the identified information requirements to build the testbed. We will build on the NIST results and refine it to facilitate the development of decision making scenarios, and also to provide the user a guideline of how to use and extend the identified information. This paper aims to answer two questions: 1) what are the information requirements in common for cross-area decision support on construction jobsite; 2) How to systematically identify the specific information requirements for a targeted decision making problem based on the built common information requirement repository.

3 DIMENSIONS OF DECISION MAKING ON CONSTRUCTION JOBSITE

A decision making task on construction jobsite can be categorized using different taxonomies, which have two major types: categorization according to attributes of decision support input/constrains and categorization using choices of decision support implementation. We summarized the taxonomies under these two major types in Table 1 and Table 2.

Table 1 shows four different ways to categorize decision making tasks on construction jobsite:

1. According to the input's origin: the input information for decision making comes from different sources, including various sensors for discrete data collection, continuous data stream, well-formed encoded documents and other documents.
2. According to the input information's imprecision: due to the various factors (e.g., device's malfunction) on construction jobsite, the data collectedfor decision making might not be perfect and theimperfect information has an impact on decision making. There are five different types of imperfect information on construction jobsites: a) imprecision types I without error. An example in crane operation safety would be the laborer's location information is missing due to signal loss; b) imprecision type II without error. An example would be an operator notices that a worker is getting too close to the crane's jib; c) imprecision combined with error. An example would be the wind speed reading when the sensor is malfunctioning; d) uncertainty. The worker's location information calculated by localization algorithm is a location with uncertainty. There is a probability distribution function of location behind it; e) inconsistency. For example, the location information collected shows that the worker is working around location A and suddenly the location information collected shows that the worker is now at location B, which is too far away from location A (the distance between A and B are far more than a human's capacity in the duration).
3. According to time requirements: some tasks related to safety issues are time critical and usually require the decision to be made in real-time or near real-time manners, while others are not time critical.
4. Application Domain: decision making task can be categorized by the domain it belongs to.

Table 2 shows three different ways to categorize decision making tasks on construction jobsite based on choices of decision support implementation:

Table 1. Decision making taxonomy based on input and constrains.

Dimension	Value	Reference
Origin	Sensor with discrete data collection (e.g., accelerometer collecting acceleration reading at a sampling rate of 1 Hz) Continuous data stream (e.g. video stream) Well formed encoded documents (e.g., xml, IFC) Other documents (e.g., CAD file, word …)	(Hu et al. 2007; IAI 2008; Mao et al. 2007)
Imprecision	Imprecision Type I without error (e.g., missing, incomplete) Imprecision Type II without error (e.g., ambiguous, fuzzy) Imprecision combined with error Uncertainty Inconsistency	(Brazdil and Clark 1990; Parsons 1996; Smets 1999)
Time requirement	Real time & Quasi real-time Short term	(Lala and Harper 1994)
Application domain	Safety management Quality management Resource management Site security management Environment management	

Table 2. Decision making taxonomy based on implementation choices.

Dimension	Value	Reference
Physical distribution of data processing/storage	Data collection device Other devices in the information transportation path End user device Centralized server	(Chong and Kumar 2003; Krishnamachari et al. 2002)
Distribution of decision making	Standalone Client-centralized server Collaborative	(Kumar et al. 2007; Panzarasa et al. 2002)
Data query	Continuous Frequent query	(Madden et al. 2002; Yao and Gehrke 2003)

1. Physical distribution of data processing and storage: where the data is processed and stored affects the energy consumption, data writing/reading speed, how quickly the decision can be made and other aspects. The decision support application developer can choose among the alternatives shown in the table (table 3) based on their consideration of devices' constrains, time requirement of decision making and origin of required information.
2. Distribution of decision making: it refers to where the decision maker and decision responder locates, as well as how they interact with each other if multiple agents are involved.
3. Data query: Data query can be continuous query, frequent query and one time only query.

4 COMMON OBJECTS REPOSITORY OF DECISION MAKING

Based on the literature review including NIST study, the authors built a common objects repository table (see table 1) to store the information requirements for decision making support on construction jobsite. The table contains two parts: part one is the first three left columns showing the categorization of common objects involved in decision making on construction jobsites, and the right two columns are the information requirements corresponding to each object on the left. The information requirements are stored in this table which can be used to help the decision making scenario developer identify the information requirements for a specific scenario. We are illustrating the table in details as follows:

4.1 *Level I: Basic production factors*

The basic production factors include people, machine, materials, environment and jobsite. Here are the descriptions of each basic production factor on jobsite:

1. People refer to all the personnel presenting on the construction jobsite, including superintendants, drivers, welders, concrete workers and others. People are the key production factor on construction jobsites and nearly all the decision making processes there involve people.
2. Machine here refers to any device that uses energy and any tool to perform construction production activity on jobsite. Machine's operation performance not only affects project schedule and quality, but also affects project cost and safety performance onsite. Monitoring machine's operation through collecting and analyzing information from them is a critical task to management team on site. It is critical to understand the information requirements for different decision making tasks with machines involved.
3. Material ranges from raw material (e.g., concrete, sand) to finished materials (e.g., precast component, steel). Materials are used/consumed by people and machine on construction jobsite, and are converted into final construction products.
4. Environment refers to the surroundings of the construction labor. Environment can impact safety, productivity and product quality in many production activities, such as crane operation, labor works in confined areas and concrete curing. Some regulations have established strict restrictions on working environments to ensure the work safety and quality on jobsite.
5. Jobsite refers to other important physical production factors that are not covered by the aforementioned categories.

4.2 *Level II: Production elements*

Level Idefines the five primary categories of common objects in decision making on construction jobsite. The five categories are generic classes of objects, and each category can be divided into several production elements. Because types of production elements (e.g., electricians, drivers, and superintendents) in people and material category have similar properties, people and material categories are not divided into detailed production elements on this level. The other three basic production factors are further divided into production elements on this level based on the reasons shown below:

1. There are many different types of machines on construction jobsite and each type of machine can be a complex system containing several sub-systems/components. Each machine type has some unique characteristics/sub-systems than others. So it would be better to divide machines on level I into specific production elements to help the decision makers better understand the required information for a specific decision task.
2. Each environment element (e.g., air, rain, soil) has unique measurement metrics whose valuesare collected from different devices. So on level II, environment in level Iis divided into several environment production elements such as air, rain, soil and others.
3. Since jobsite on level I is a relatively vague concept, it should be divided into concrete elements at this level. The elements in jobsite category include Area, Floor Plan, Schedule and other.

4.3 *Level III: Components of production elements*

The production elements under machine category in level I can be further divided into sub-systems/production components as described in last section. For example (see table 3), tower crane on level II can be divided into components including(but not limited) to rotating base, main jib, counterweight jib, counter weight, trolley, hoisting pope, hook and tower mast.

4.4 *Information, relevant data and possible data sources*

After establishing the repository of common objects in decision making on jobsite, relevant information, data and possible data sources are then identified for each end node in the tree-shape structure in Table 3. Relevant information refers to the useful knowledge which might be useful for decision tasks involving the objects. Relevant data means the raw pieces of knowledge which can be directly collected through observation and recordkeeping. Data can be converted into information through data manipulation (e.g., combination). Possible sources are

Table 3. Repository of required information of common objects in decision making on construction jobsite (partial).

Basic production factor	Production element	Component of production element	Relevant information	Relevant data	Possible source
People			Unique ID	ID #	RFID
			Location	X, y, z value	RFID, GPS, Crickets
Equipment	Tower crane		Unique ID		RFID
			Base location		Database/RFID
			Height		Database/FRID/GPS
			Lifting capacity		Database/RFID
			Authorized drivers	Lists of drivers ID#	Database
			Operating speed requirements	Speed	Operating speed limits
		Main JIB	Length		Database
			Angle	In x-y, x-z, y-z plane	Angle Sensor
		Counterweight JIB	Length		Database
		Counterweight	Weight		Load sensor
		Trolley	Radius/distance from the tower session		Cable length sensor
		Hook	Load		Load sensor
Material			Stack unique ID		RFID, bar code
			Location	X, y, z value	RFID, GPS, Crickets
Environment	Air	Wind	Measurement location	X, y, z value	RFID/Database
			Speed		Windsock sensor
Jobsite	Area		Boundary	Array of points	BIM, CAD file
			Area type (authorized only, dangerous, etc.)		Database

identified for each piece of data/information in the table through brainstorming and literature reviews.

Elements in level 1 to level 3 and their corresponding relevant information, data and possible data source are recorded into a repository table similar to table 3, which is part of the larger and complete repository table.

5 IDENTIFYING INFORMATION REQUIREMENTS FOR DECISION MAKING

The decision making scenario developer can use the common objects repository table to systematically determine the information requirements for a specific scenario. When the developer determines the decision making problem for analysis, he/she first decides which field the decision making problem falls into. Based on the identified field, the developer can refer to the existing information requirement analyses under the same field category and use them as examples. Then, the developer should go to the repository table (table 3) and pick the basic production factors related to the decision making problem. Consequently, they can identify the related production elements under each basic production factor using table 3. Within each identified production element, the decision scenario developer further determines the specific components of production element if applicable. At this moment, the scenario developer has identified all the relevant elements from level I to level III in table 3. As a result, the developer can use table 3 and go through the relevant information column to choose all the relevant information required for the decision making process. The result would be a list of primary information needed for the decision making process.

6 DEMONSTRATION

6.1 *Scenario description*

In this paper, we chose todemonstrate the scenario development framework and information requirement identification through the decision making processin atower crane's safe operation, since this example covers a wide range across the dimensions in table 1 and table 2. For example, it uses discrete data from sensors, stream data from video camera and information (e.g., the geometric boundary information of a dangerous area which might be stored in IFC using IfcBoundedCurve, as well as the semantic information like material type) from a building information model (BIM). Also, data can be processed on the sensor, sensors on the data transportation path, end user device (e.g., PDA) and centralized server (e.g., server in the project management office). We made a simplified abstraction of the tower crane operation to highlightits primary characteristics, and to demonstrate how to use our repository of common objects and relevant information to develop the decision making scenario and identify required information. Figure 1 shows the simplified operation process of the tower crane on jobsite in a work shift. At the beginning of the work shift, the tower crane is powered off. The crane operator needs to check the current and forecast wind speed for the operating period,making sure it is safe for crane operation before powering up the crane. After the crane is powered up, the crane enters the state of "power on at original position". Then the operator repositions the crane to the location (load origin) where the load is waiting for the tower crane to move it to its destination. The crane lifts the load at its origin and then repositions/moves itto the load's destination. When the load arrives over the load destination, the crane lowers the load and repositions to the next load origin where the lifting and repositioning process repeats until the end of the work shift. At the end of the work shift, after making sure that the crane is empty loaded, the operator repositions the crane to the resting position and powers off the crane.

6.2 *Identifying the required information for decision making process*

Since we focus on the tower crane operation safety during decision making in this scenario development process, here we are only going to identify the objects and required information relevant to crane safety.

First, we determine that the crane safety involves all the five basic production factors shown in table 3.

Secondly, we need to determine what production elements in level 2 (see table 3) are related to the decision process:

- In the machine category, "tower crane" is the only production element involved in the decision making process (we do not consider anti-collision between tower crane and other operating equipments to simplify the decision making scenario. Therefore, other equipments are not considered here).
- In the environment category, air and rain/snow affects the decision making process regarding crane operation process, because it is not recommended to operate tower crane in strong wind, heavy rain or heavy snow weather (OSHA 2008).
- In the jobsite category, area is an important factor which needs to be thoroughly considered to ensure crane operation safety. Occupational Safety and Health Administration (OSHA), American Society of Mechanical Engineers (ASME) and other

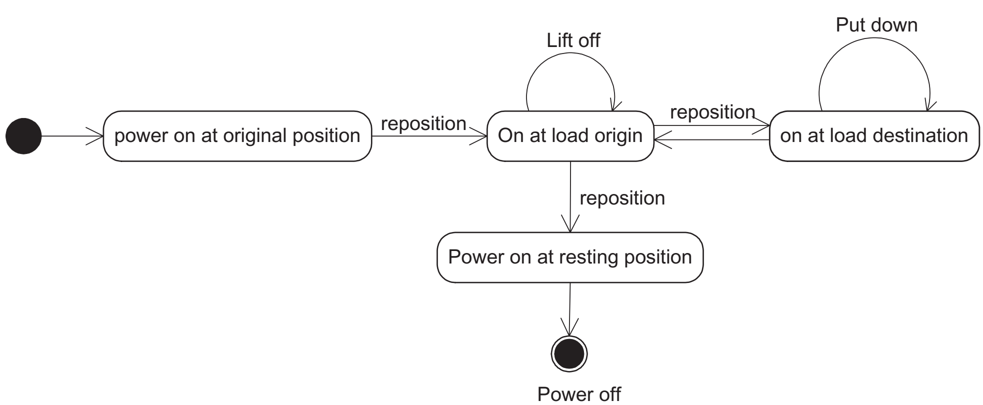

Figure 1. State diagram of tower crane operation.

organizations have forbidden the tower crane from entering some restricted areas. For example, tower crane's component should keep off from the power line for at least 15 feet.

Thirdly, as tower crane is a complex system, we need to further divide it into several relevant components. Tower crane consists of many pieces and we only consider some important components (rotating base, main jib, trolley and hook) among them because they are critical to crane safety.

The final step is identifying the required information under the selected elements in level I, II and III in the aforementioned three steps. We review all the possible information and relevant data listed under the identified components in table 3. The relevant information and data is shown in table 3. At this moment, we can get most of the information needed for decision making process of tower crane safety. The possible data sources also provide the user where they can get the required data with possible sources and what devices are needed to collect data.

6.3 *Building decision making scenario based on identified required information*

We selected the presentation "Site Safety in Crane Operation"(Ocharsky 2009), which covers the primary issues on tower crane safety in construction practice, as a source of decision rules to build the decision making scenario. We went through the presentation and filtered out the sentences that are relevant to the identified basic production factors, elements and components as follows:

- No crane or derrick operator shall start an operation when the wind speed exceeds 30 M.P.H., or when the wind is predicted to reach 30 M.P.H. before the operation can be completed.
- In rigging safety: ensure that area is clear of personnel;
- Never lift people or never ride hoisting load;
- Never load over people;
- Never lift the load over rated capacity;
- No hoisting over occupied buildings, pedestrian or vehicular traffic;
- Electrical power line—min 15 feet;

For each sentence above, we can translate it into decision rules. For example, the first quoted sentence above can be translated into decision rule as follows:

Input information	Decision node	Output information
Wind speed	Compare wind speed and constant value of 30 M.P.H.	Warning information or approval

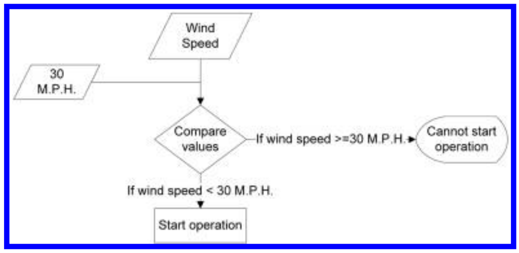

Figure 2. Decision tree expression of decision rule #1.

The decision rule can be also expressed as Figure 2:

By repeating the same process for each sentence picked out as aforementioned, we can establish a decision rule repository containing decision rules as the example above. The following step is that we review each decision rule in the repository and determine which state/transition the decision rule locates in. Then the decision rule is added into the state diagram. By repeating the process, we establish a new state diagram (Figure 3) to illustrate the decision making process for tower crane's safe operation.

7 DISCUSSIONS AND CONCLUSION

This paper has established a structured repository of required information for sensor-assisted decision making on construction jobsite. The repository contains three layers of objects involved in decision making, and the authors identify the required information and data based on reviewing literature about using sensors to support decision making on jobsite. The repository also provides possible sources to look for and collect the required information/data. In this paper, the authors show the decision making scenario developers a systematic way to identify the required information for the targeted decision making problem.

The research demonstrates the procedure to use the established repository for identifying the required information for a tower crane operation scenario. To show the advantages of identifying required information for decision making process, the paper also demonstrates how to use identified information to build the complete decision making scenario for tower crane operation safety. The built decision making scenario can be later employed to assist the application developers for programming. However, the result of the demonstration has not yet been reviewed by the industry experts, and it will be helpful to invite them as well as peer-researchers to review the result for further revision. Such validation will be carried out at a later stage.

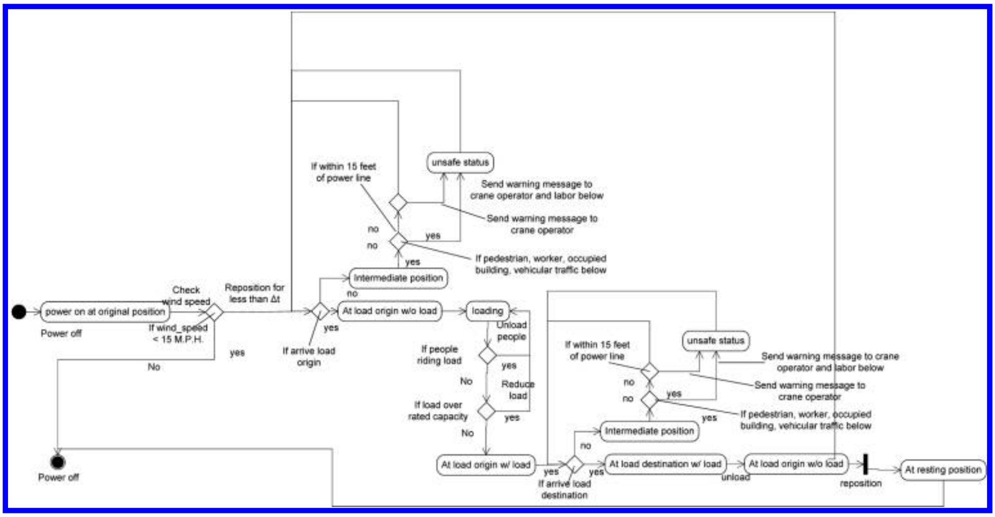

Figure 3. State diagram with embedded decision rules.

Based on the developed repository of required information for decision making on construction jobsite, future research might include: 1) a study on the quality of information from different sources in the repository; 2) decision making with dirty information; 3) general decision rules/reasoning mechanisms applicable for various tasks/domains; 4) a systematic way to analyze and build the decision making scenario to support the decision support applications' development.In next step of the research, we will select several decision making scenarios which covers the full range in the n-dimensional spaces using table 1 and table 2. These scenarios will be carefully studied to extract the commonalities of input information, decision rules inside and the quality of input data. Based on the analysis of input data's quality, we will refine methods dealing with these data with different qualities based on existing techniques.

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Exploring the influence of media richness on engineering task performance and user perceptions

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ABSTRACT: The task-technology fit and the perceived usefulness and ease of use of an engineering Decision Support System (DSS) are important antecedents of the systems successful implementation. At the same time, both task-technology fit and perceptions of ease of use and usefulness are related to the media richness of the system's graphical user interface. This paper explores the influence of media-richness on task-performance and perceptions of users by presenting the results of a lab experiment with Bachelor students from a Dutch university. The outcomes of the experiment show that independent of the task-technology fit of the DSS, students perceived the usefulness and ease of use of the media rich DSS higher than that of the media poor DSS. These findings have important implications for engineering managers that wish to implement a DSS in their organization and for developers and designer of user interfaces for engineering DSS.

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1 INTRODUCTION

With the advent of more and more engineering decision support systems (DSS), software designers face a new challenge: how to best present information to support engineers with their decision making tasks. Most existing DSS provide a vast amount of different possibilities to display simulation and analysis results using media rich representations. Previous research showed that an increase in media richness has positive effects on perceived task fit and usefulness. It is, however, questionable whether an increase in media richness will actually increase "real" task performance. While the perception of the usefulness of a technology is an important predictor towards a later application of the technology, the increase of media richness of applications also increases the costs of development. Little is known today about how software developers can best balance this paradox.

To advance this knowledge with an understanding about the underlying psychological dynamics of how media richness influences engineers, this paper presents the outcomes of a lab experiment that we conducted with a group of engineering Bachelor students. In the experiment, we asked part of the participants to conduct an engineering task using a media rich application and the other part to conduct the same task using a media poor application. We used a previously prepared metrics to measure the "real" task performance of the participants. We also asked participants before and after the experiment to report about their perception of the task technology fit of the application and their perception about the usefulness. This paper compares the answers of the two participant groups with the "real" task performance of the participants and critically analyses the results of this comparison.

The paper is structured as follows: It starts with a brief introduction in media richness theory, task technology fit theory, and introduces perceived usefulness and ease of use as one of the theoretical predictors of later use. Based on this theory the paper then derives the hypothesis that independent of the task-technology fit, media richer DSS are perceived as more useful and easier to use. After briefly describing the experimental setup, the paper continues with presenting a statistical analysis of the experiment results. Finally, the paper discusses this analysis and develops a number of theoretical implications for the implementation and development of engineering visualization and simulation tools.

2 TASK TECHNOLOGY FIT, THE TECHNOLOGY ACCEPTANCE MODEL, AND MEDIA RICHNESS

To have a positive impact on performance, engineers must use a DSS and the DSS must present a good fit with the tasks the engineer intends to support (Goodhue & Thompson 1995). To achieve such a good fit for a DSS that allows the support of engineering design work, technology developers and researchers need to align (1) the DSS functions and features and (2) the user interfaces that allow engineers to enter input data and that allow engineers to quickly analyze and understand the output of the DSS.

A good concept to understand the influence of a DSS's user interface on task technology fit is media richness. In its original form, media richness theory proposes that organizations strive to accomplish task-technology fit by adjusting the requirements of data communication tasks with the capacity of the media. Initially media richness theory focused on non-electronic media and on communication between humans (Daft & Lengel 1986), however, media richness theory is also a valuable concept to understand human-computer interaction. This paper, therefore, uses media richness theory to explain and predict the influence of user interfaces on task technology fit. We postulate that the right adjustment of the media richness of an engineering DSS with the engineering analysis task at hand helps engineers to understand DSS output rapidly, handle different indicators to enable multi-criteria design decisions, and allows to focus on important output parameters. Misalignments of media richness of the user interface and the task can either be caused by user interfaces that are too media rich or not media rich enough. Interfaces that are too media rich for the task at hand will cause information overload that hinders engineers to quickly understand the DSS output. Interfaces that are not media rich enough might present DSS outputs too complicated and too ambiguous to allow for an easy understanding.

Next to influencing the fit between a DSS and the engineering task at hand, the paper also postulates that media richness influences the perceptions of the user with respect to the usefulness and the ease of use of the application. The two concepts usefulness and ease of use of a certain computer application are at the core of the technology acceptance model (TAM) that explains how potential technology users come to their decision to adopt a specific technology (Davis 1989). The model assumes that the respective user's perceptions about the usefulness and the ease of use of the application will influence the decisions of the user to later adopt and apply the technology.

Many researcher have replicated the TAM model in a broad range of technology implementation settings (see for example Adams et al. 1992). These replication of studies has led to the development of reliable instruments to measure the perceived usefulness and ease of use of a software application. All this together has caused the TAM model to become one of the most influential models in management information science research. TAM provides a general explanation of how users accept computer technologies. The model can explain user behaviors across a broad range of users and for a large number of different end-user computer applications (Davis et al. 1993). Technology managers can, therefore, use the TAM model to predict whether a new technology is acceptable for end-users and can diagnose the reasons why a new technology may not be fully acceptable. This allows managers then to take corrective actions to increase the acceptability of the system.

3 RESEARCH HYPOTHESIS

Dishaw and Strong (1999) empirically showed that for the successful and sustainable implementation of a technology both user acceptance and task technology fit are important antecedents. The previous section theorized that the media-richness of the user interface of the DSS influences not only task-technology fit, but also the engineer's perceptions about usefulness and ease-of-use of the DSS. This paper provides a empirical exploration of the influence of a DSS media richness on user perception and how this relationship is mediated by task technology fit. To do so, the paper tests the following hypothesis:

A higher media richness of an engineering decision support system is positively related with (a) perceived usefulness and (b) ease of use independent of the task technology fit of the application.

To test the hypothesis we conducted an experiment with engineering students of a Dutch university. The next section describes the experimental setup in detail.

4 EXPERIMENTAL SETUP AND ANALYSIS STRATEGY

To test the two hypotheses above, we conducted an experiment with a class of Dutch Bachelor students. The experiment centered around the task to identify design conflicts within the multi-disciplinary design documents of a recently built office building. The overall office building provided approximately 1,500 square meters of office space over three levels and was completed in 2009 in the Dutch city of Zwolle.

The detection of design conflicts was an important step during the coordination of the designs for different sub-systems of the building (Staub-French & Khanzode 2007). In current practice, different parties design these different subsystems of a building. The integration of these independent sub-system designs into a consistent overall design is a challenging task because of the existence of so called clashes between the different systems—physical inconsistencies of two sub-systems that, by design, allocate the same space. If such clashes are not found during the design coordination efforts, they will lead to delays and cost overruns later on during the physical construction of the building Traditionally, practitioners coordinated designs by comparing 2D drawings delivered by the different discipline designers. Lately, software companies have introduced media-rich decision support systems that promise to help designers with the detection of conflicts. These applications allow the combination of three dimensional computer models of the different sub-system designs and provide clash detection algorithms that can automatically detect clashes.

At the start of the experiment, we divided the students in three groups. We provided each student of the first group with the original set of drawings of the office building process that were provided by the different design parties. These drawings included the designs of the architectural, structural, and building installation systems. Overall, each student in this group received 42 different drawing sheets in the form of DIN A3 print outs. 2D drawings are a relative static medium to communicate design details. We assume that these drawings, therefore, represent a DSS with little media richness (Figure 1).

We provided each student of the second group with a 3D model of the same building design loaded in the automated clash detection software Navisworks from Autodesk. This 3D model represented the model a designer of the project had created to support the design coordination on the project. The model consists of approx. 3000 3D model objects of different building components, such as walls, columns, ducts, or cable trays, that embody all relevant systems represented by the 2D drawings we gave to the first group of students. Before the experiment we had organized the model

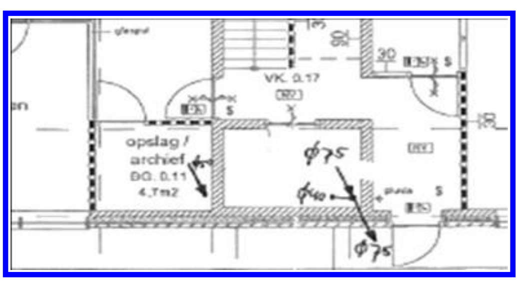

Figure 1. Representation of clashes with media-poor 2D engineering drawings.

to allow students to easily find relevant clashes. To do so, we chose a break down structure that we based on a simplified version of the Dutch classification norm's NEN 2634 third detail level. Overall, we organized all objects into nine groups among which the most clashes during the construction of the building occurred. Table 1 describes the break down structure and the classification codes we used for the model organization. We then used the functionality of the clash detection software to group the 3D model's objects into different systems. This allowed students to select and automatically clash different systems that were developed by different designers. Figure 2 illustrates how this media-rich tool represents clashes as 3D representations of building components.

Finally, we provided each student of the third group of students with the same clash detection software than the second group. However, the 3D model of the office building of this group was not organized to allow for the easy detection of clashes. Therefore, the model was not specifically fitted to the task at hand and allowed for a comparison of the influence of task technology fit on user perceptions of usefulness and ease of use.

Before the start of the experiment we provided the students with a number of documents to help them get started with the identification of clashes. Independent of the group membership of the students, we also handed out a general guideline document. We prepared this guideline document together

Table 1. Object groups we used to organize the 3D model.

Trade	Code NEN 2634	Description of the object group
A		Architect
A	2	Construction works
A	2C	Roofs
A	2D	Facades
A	2E	Internal walls
A	2F	Floors
A	2G	Escalators
A	2H	Ceilings
A	3	Installations
A	3C	Elevator and transport
C		Structural Engineer
C	2	Construction
C	2A	Foundation
C	2B	Framework
I		Installer
I	3	Installations
I	3A	Mechanical installations
I	3B	Electrotechnical installations

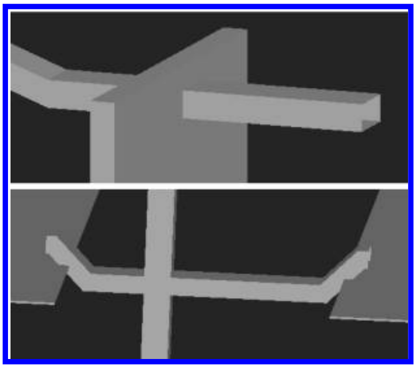

Figure 2. Two clashes represented in the media-rich 3D clash detection software application. The figure above shows a clash between a ventilation shaft and a supporting wall. The figure below illustrates a clash between a ventilation shaft and a false ceiling.

with an experienced design coordinator—the same coordinator that had coordinated the designs for the office building we used for this experiment. In particular, the guidelines recommended that students only look for clashes that will result in change orders during the construction phase and that these clashes usually occur between elements designed by different design parties. Additionally, we provided the students that used the automated clash detection application with a short introductory video of how to generally use the clash detection application, and how to, in particular, clash objects of different systems.

We gave each student one hour time to detect clashes in the design individually. To track the results, we asked each student to fill in a table with "the location", "the names of the elements", "the elements' ID", "the elements' participants", and "the distance of overlap" of the clashes they found.

To measure the students perceptions of ease of use and usefulness we also asked each student to fill out a survey before and after the experiment. The survey used a slightly adjusted form of Davis' (1989) measurement instrument that has been applied by a number of previous studies and is, therefore, well tested and validated (for the survey instrument see Appendix A at the end of the paper).

To understand the influence of the respective media on the students' perceptions of ease of use and usefulness, we were in particular interested in how the perceptions of the students changed after the experiment. Therefore, we compared the answers of the students before and after the experiment. To do so, we calculated the difference between how students rated the usefulness and ease of use of the method before and after.

After the experiment we analyzed the data by first identifying the number of relevant clashes each group of students found in the model. To do so, we compiled a list of problems that occurred during the construction of the office building that either caused delays of the construction work or cost overruns and that were caused by physical inconsistencies in the original design drawings. We then compared each of the clashes students found during the experiment with the clashes in the list. We labeled all clashes that students found that had caused some problems, delays, or cost overruns during the real construction of the building or not. During our analysis we then used the number of relevant clashes that students found as a measure for the "usefulness" of the respective media we provided the students.

5 RESULTS

To ensure the validity of the analysis results we first compared the two student groups according to a number of control variables that we included in the survey that we conducted before the experiment. None of the students had ever used the clash detection software Navisworks before the experiment and only one of the students reported that he had seen Navisworks. Students also reported about the time they spend each week using a computer on a three point scale (1 = 10 h or less; 2 = 10–20 h; 3 = more than 20 h) and they rated their skill of reading 2D construction drawings on a 7-point Likert scale. An initial ANOVA test for a difference of these values among the groups did not provide significant differences between the mean scores of the groups so that we assume a relatively even distribution of computer skills and skills to read drawings among the students and groups.

We then analyzed the in between group difference of the means of the detected relevant clashes and the difference in scores on perceived use and usefulness before and after the experiment for the groups that used the 2D drawings and Navisworks with the organized model. Table 2 summarizes this difference. The results show that the average of found relevant clashes is similar between both groups. The groups that used the Navisworks software was not significantly more effective in detecting the relevant clashes than the group that used the 2D drawings. Despite this apparent similarity, the group that used the 2D drawings for this task rated the usefulness and the ease of use of the 2D drawings significantly less than the group that applied the Navisworks software. As expected, there is not much difference in how both groups rated the usefulness and ease of use of the Navisworks software before and after the experiment.

Afterwards we analyzed the in between group difference of the means of the detected clashes and the difference in scores on perceived use and

Table 2. Comparison of means between students that used 2D drawings and students that applied Navisworks.

	# Relevant Clashes	Difference in perceptions 2D drawings		Difference in perceptions navisworks	
		Usefulness	Ease of use	Usefulness	Ease of use
2D Drawing group	1.69	–1.2692	–1.1538	0.2436	0.1538
Navisworks group	1.63	–0.3158	–0.3596	0.1491	–0.0614
Statistical significance of difference (T-Test, p = 0.05)	No	Yes	Yes	No	No

Table 3. Comparison of means between students that used the organized model and staudents that used the unorganized model in Navisworks.

	# Relevant clashes	Difference in perceptions 2D Drawings		Difference in perceptions Navisworks	
		Usefulness	Ease of use	Usefulness	Ease of use
Organized model group	1.63	–0.32	–0.36	0.15	–0.06
Unorganized model group	1.00	–0.79	–0.56	0.12	–0.63
Statistical significance of difference (T-Test, p = 0.05)	Yes	No	No	No	No

usefulness before and after the experiment for the groups that used the two different models in Navisworks. Table 3 summarizes this difference. The results show that the group with the organized model found significantly more clashes than the group with the non-organized one. Despite this difference in task performance of the two groups, there is no significant difference in the difference of perceptions before and after the experiment. It is quite surprising that the group that used the unorganized model even rated the usefulness and ease-of-use of the 2D drawings on average worse than the group that used the organized model.

The next section will discuss the implications of these interesting findings with respect to the development and implementation of engineering simulation tools.

6 IMPLICATIONS

Our results provide empirical evidence for the paper's hypothesis. The results show that independent from the task effectiveness of media rich applications, the media richness influences the perceptions of users about the usefulness and ease of use of a specific engineering application significantly. This finding adds a new angle on the existing research around the effect of media richness. While previous research has mainly looked at how to best adjust media richness with tasks at hand, this study shows how media richness, independent of task-technology fit influences user perceptions with respect to ease of use and usefulness of engineering applications.

The findings can help researchers and engineering application developers to understand the effects of different user interfaces on engineering performance and the acceptance of applications by engineers. On one hand, the media richness of graphical user interfaces should be aligned with the engineering task at hand. Too little or too much media richness of the graphical user interface can hinder the engineering task performance. At the same time, however, the media richness of an engineering application will influence the perception of the user about the usefulness and ease of use of the application. Engineers will perceive media rich applications as more useful and as easier to use even if the graphical user interface is media richer than the task at hand requires. Interface designers for engineering applications need to find a good balance between task-technology fit, media richness, and user acceptance while designing user interfaces

The findings of the paper also have implications for engineering managers that wish to implement engineering applications in their organizations. Engineering managers should thoroughly evaluate whether the media richness of the graphical user interface of the application is aligned with the engineering tasks at hand. In the same line, however, they need to be aware, in particular, during the early decision phases of whether to adopt a new engineering application or not, that they may perceive media rich applications as more useful than they really are. Overall, engineering managers should be especially cautious while they judge the potential to improve engineering task performance if they are evaluating media rich applications.

The findings of this paper further have a number of implications for researchers in the area of engineering informatics. First, researchers should be aware of the fact that by providing media richer user interfaces for their research prototypes they can directly influence the acceptance of their research results by their peers and more importantly by practitioners. Researchers that plan to make an impact with their research results should thus provide a media rich user interface for their developed technology prototypes. Even more importantly researchers should be aware of the findings of this research while using expert opinions to validate their research prototypes. How experts rate the increased engineering task performance new engineering DSS offers, might be heavily influenced by the media richness of the graphical user interface of the system. Even if the system does not directly increase engineering task performance our findings suggest that engineers still perceive media richer systems as more useful. One way for researchers to circumvent this possible bias during the validation of their research results is to develop user interfaces for research prototypes with different media richness. In this way researchers can compare the expert ratings of engineers that used different user interfaces and can normalize biases in the validation results that might have been caused by the media richness of the prototype's user interface.

7 SUGGESTIONS FOR FUTURE RESEARCH

How relevant the paper's findings are within practical settings remains questionable and only similar experiments that test for a number of other possible mediating factors can provide an answer to this questions. It would, for example, be interesting to see how different expertise levels of participants would change the results of the experiment. In the here presented experiment none of the participants had any significant experience with reading drawings or with using automated clash detection software. All experiment participants were students with very little or none practical experience. We suggest that researchers should repeat the experiment with practitioners to understand how experience levels influence the results.

Further, it would be interesting to explore how project complexity influences the outcomes of the experiment. Currently, the experiment is based on a relatively simple office building. Much of the literature that has described the required media richness to complete a task on the relative task complexity (Daft & Lengel 1986). It would be interesting to see if the outcomes of the experiment would change if researchers would repeat the experiment using a more complex building as underlying case and increase the task complexity in this way.

Finally, it would be interesting to explore the influence of different user interfaces of clash detection applications on the experiment results. Not all results of the experiment might be caused by the media-rich presentation of the 3D models itself, but also by the design of user interfaces to conduct the automated clash detection procedures. Such experiments could then, in turn, yield valuable findings about how to best develop clash detection programs and user interfaces.

Next to conducting such further experiments that test the effect of certain variables on technology acceptance of users in isolation, researchers should also follow practitioners closely and critically while they use clash detection technologies with different media-richness. Such ethnographic efforts will yield additional in depth findings that account for the real world complexities that practitioners encounter in project settings and that can complement the results of lab experiments, such as the one presented here.

Despite, the many different other mediating factors that might have a practical relevance, we designed the here presented experiment to resemble practical engineering tasks as closely as possible. The experiment's task represents a task that engineers have to perform on every construction design project. Further, the case we used for the experiment is a real world case and uses real world engineering data and documents. We expect that the results of the experiment are, therefore, very well relevant for engineering practice.

8 CONCLUSION

This paper presents the outcomes of a lab experiment with engineering Bachelor students of a Dutch university. During the experiment three different students conducted an engineering design task. Each of the groups used a different engineering DSS with respect to the DSS's media richness. The first group used a traditional set of drawings, the second group used a 3D visualization and analysis tool, and the third group of students used the same visualization and analysis tool then the second group that we adjusted to decrease its task-technology fit. The outcomes of the experiment show that independent from the task-technology fit of the application the students perceived the usefulness and ease of use of the media-rich DSS superior than the ease-of-use and usefulness of the media-poor DSS.

The results of this experiment have important implications for engineering technology managers, engineering researchers and developers of user interfaces for engineering DSS. Managers and researchers need to account for the influence of the media richness of a DSS on user perceptions while they are evaluating or validating the usefulness of a certain DSS. Developers of user interfaces for engineering DSS need to carefully balance the media richness of a user interface. On one hand, it does not mean that a media rich application improves the task performance of engineers. More media rich application actually might cause information overload and even hinder the engineer's performance. On the other, the media richness of an application influences the perceptions of users about their usefulness and ease-of-use and thus might be an important factor during the adoption of a new engineering DSS. The findings from this paper provide a first starting point to better understand how to balance this paradox while designing user interfaces for engineering applications.

ACKNOWLEDGMENTS

We would like to thank the Bachelor class of the University of Twente that participated in the experiment. Additionally, we would like to thank Nico Bursema and Hans Hendriks from BAZ in Zwolle, The Netherlands that gave us access to all project information that was necessary to conduct the here presented experiment.

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APPENDIX A: SURVEY INSTRUMENT

Imagine that your later job will be project coordinator and your main task is to care for the integration of the different specialty designs of a project. Please answer the following questions:

(Ease of Use Navisoworks)

1. Using Navisworks in my job will enable me to accomplish tasks faster
2. Using Navisworks will improve my job performance
3. Using Navisworks in my job will increase my productivity
4. Using Navisworks will enhance my effectiveness on the job
5. Using Navisworks will make it easier to do my job
6. I will find Navisworks useful in my job.

(Usefulness Navisworks)

1. Learning to use Navisworks will be easy for me
2. I will find it easy to get Navisworks to do what I want
3. My interaction with Navisworks will be clear and understandable
4. I will find Navisworks flexible to interact with
5. It will be easy for me to become skillful at using Navisworks
6. I will find Navisworks easy to use.

Now please answer the same questions with respect to 2D drawings!

(Ease of Use 2D Drawings)

1. Using 2D drawings in my job will enable me to accomplish tasks faster
2. Using 2D drawings will improve my job performance
3. Using 2D drawings in my job will increase my productivity
4. Using 2D drawings will enhance my effectiveness on the job
5. Using 2D drawings will make it easier to do my job
6. I will find 2D drawings useful in my job.

(Usefulness of 2D drawings)

1. Learning to use 2D drawings will be easy for me
2. I will find it easy to get the needed information from 2D drawings
3. My interaction 2D drawings will be clear and understandable
4. I will find 2D drawings flexible to interact with
5. It will be easy for me to become skillful at using 2D drawings
6. I will find 2D drawings easy to use.

Hardware-Software platforms for facilities and energy management

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Development of miniaturized wireless sensor nodes suitable for building energy management and modelling

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ABSTRACT: Buildings consume 40% of Ireland's total annual energy translating to €3.5 billion (2004). The EPBD directive (effective January 2003) places an onus on all member states to rate the energy performance of all buildings in excess of 50 m^2. Energy and environmental performance management systems for buildings generally and consist of an ad-hoc integration of wired building management systems and monitoring and targeting systems. These systems are unsophisticated and do not easily lend themselves to cost effective retrofit or integration with other enterprise management systems. Building Information Models (BIM) consists of two major components: a three dimensional graphical reproduction of the building geometry and a related database in which all data, properties, relations are stored however the data sets required to develop these models does not generally exist. It is commonly agreed that a 15–40% reduction of building energy consumption is achievable by efficiently operating buildings when compared with typical practice. Existing research has identified that the level of information available to Building Managers with existing Building Management Systems and Environmental Monitoring Systems (BMS/EMS) is insufficient to perform the required performance based building assessment. The cost of installing additional sensors and meters is extremely high, primarily due to the estimated cost of wiring and the needed labour. From this perspective wireless sensor technology provides the capability to provide reliable sensor data at the required temporal and spatial granularity associated with building energy management. In this paper, a wireless sensor network mote hardware design and implementation is presented for a building energy management application. Appropriate sensors were selected and interfaced with the developed system based on user requirements to meet both the building monitoring and metering requirements. Besides the sensing capability, actuation and interfacing to external meters/sensors are provided to perform different management control and data recording tasks associated with minimisation of energy consumption in the built environment and the development of appropriate Building Information Models (BIM) to enable the design and development of energy efficient spaces.

1 INTRODUCTION

Traditionally building automation systems are realized through wired communications. However, wired automation systems require expensive communication cables to be installed and regularly maintained and thus are not suitable for many retro fit applications of sensor technologies [1, 2]. For example, the installation cost of a light switch in a building facility can be as high as 10–30 times the cost of the switch; this estimate does not include the possibility of additional work such as conduit installation and infrastructure work.

In recent years, wireless technologies have become very popular in a wide variety of applications spaces, for fitness and health monitoring, environmental monitoring and other both home and commercial networking applications.

In particular, the use of wireless technologies offers distinctive advantages in the field of home and building automation [3–5] as installation costs are significantly reduced since no cabling is necessary, and neither conduits nor cable trays are required. Wireless technology also allows the placement of sensors where cabling is not appropriate for aesthetic, conservation or reasons of safety [4, 5].

Wireless sensor networks are required to have extended lifetime in deployment, be rugged, reliable robust and be easy to deploy by non technical personnel in the field. The requirement for extended lifetime deployments requires that low power design starts with the obligatory use of energy efficient hardware (e.g., low supply voltages and support for sleep modes in microcontrollers) [6].

A Building Information Model (BIM) consists of two major components: a three dimensional graphical reproduction of the building geometry and a related database in which all data, properties, relations are stored.

The value of BIM created during design and construction phase is well documented and can result in an estimated 30 percent reduction in total construction costs. Throughout the typical Building Life Cycle there are series of discontinuities in the transmission of building data that occur. Transitions from design to construction to operation result in loss of data, added cost to reconstitute the data, and overall reduction in data integrity. The impact, growing at each handover, culminates with the handover to the facility operator and therefore to the energy manager. This paper is focussed on the development and deployment of a miniaturized Wireless Sensor system for building sensing, meter interfacing and actuation and the development of building models with the data sets delivered.

2 WSN NODE DESIGN

2.1 *System Architecture and functional units*

The Building Energy Management "mote" is designed in modular mode to enable the addition and interfacing of additional functionality as required and is based around the Tyndall Institutes modular prototyping system for sensor networks. As Figure 1 shows, the system contains four main sections, these are the data processing section, the RF communication section, sensors/meters and actuation section and the power supply management section.

The multi-sensor layer was designed to interface with a number of selected sensors as well as incorporating additional capability for use within the building environment. This includes dual actuation capabilities for any AC/DC system using an external high power relay based system for devices which consume up to 280 V and 25 A (to turn on and off appliances) as well as an onboard low power switch to enable the actuation facility. The on-board sensors are either digital communicating with the microcontroller through serial bus interface like I^2C or analogue connected with any of the ADC channels.

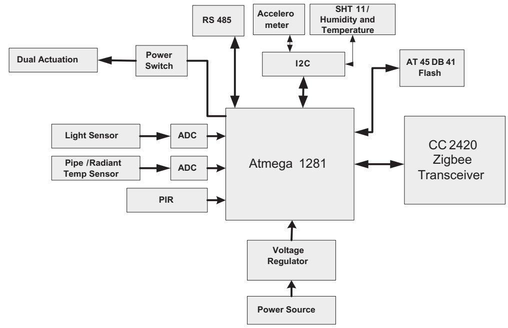

Figure 1. Block diagram of the WSN mote.

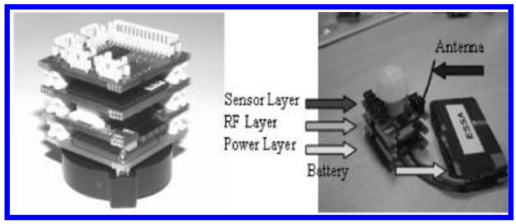

Figure 2. Modular sensing system developed for BEM deployment.

The two external sensor/meter interfaces are dedicated to any meter using MODBUS protocol [7] and variable resistance temperature sensors. The MODBUS meter is exchanging data/commands through RS485 serial communications.

This interface layer was also designed to incorporate external flash memory (Atmel AT45DB041). The layer features a 4-Mbit serial flash for storing data, measurements, and remote re-programming. An image of the modular sensing system developed for BEM deployment is shown in Figure 2.

3 SENSORS SELECTION

Based on the user requirements as regards data sets which were needed to develop the Building information models for the buildings under investigation, a variety of sensors were selected and appropriate interfaces developed for deployment in the wireless sensor network. The data sets from these sensor were then used to augment the data sets from standard wired Building management systems.

Table 1. The comparison of the AMN44122 PIR sensor with reference to date sheet.

Items	Data sheet	Lab test
Detection Limits	10 m (32.808 ft)	9 m (29.528 ft)
Horizontal	110°	90°
Vertical	93°	90°

3.1 *Occupation sensor (Passive Infrared PIR)*

Detecting occupancy parameters of the rooms in the building was identified as being essential in the development of energy consumption rates and trends. A PIR sensor module—the Panasonic AMN44122 [8] was selected for this purpose since it provides a small form factor, low power consumption solution. The module provides a digital detection output that can be used to trigger an interrupt on the processor when activity registers on the sensor. The detection limits of the sensor in deployment are as in Table 1.

3.2 *Humidity/Temperature/Light sensor*

Relative Humidity (RH) is an important indicator of air quality in buildings. Extremely low or high humidity levels (the comfort range is 30–70% RH) can cause discomfort to workers as well as increasing its overall energy consumption levels. The Temperature and Humidity sensor SHT11 [9] was used on the sensor board which integrates signal processing, tiny foot print and provide a fully calibrated digital output. It uses I²C serial interface to communicate with the microcontroller and provide either the humidity or temperature data based on the received commands.

A miniaturized photo diode with output current proportional to ambient light level conditions was used to measure the amount light LUX levels present in the building.

3.3 *Windows/Doors status monitoring*

The detection of the windows/doors status was one of the building parameters required to be monitored by the WSN node. A 3-axis accelerometer was selected for this application since it can provide useful angle information which helps to know how wide door/window is opened or closed. The LIS302DL is an ultra compact low-power three axis linear accelerometer which was integrated in the node design [10].

The main design challenge with using the accelerometer is that the microcontroller has to be continuously active to record sensor data which means high current consumption and short battery life time. In order to overcome this problem, a mechanical vibration sensor with very small footprint was used in this design to provide an external interrupt to the Atmel microcontroller when there is any kind of motion as presented by Figure 3.

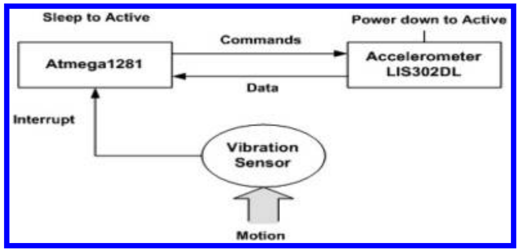

Figure 3. Functional block diagram of the motion sensor design.

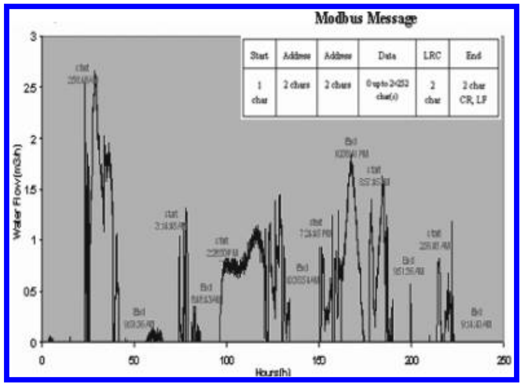

Figure 4. Water flow rate measurements.

3.4 *Water flow metering in heating circuits*

It is required to get the flow rate measurements from different locations inside the building where pipes made from different materials and have wide scale diameter size to evaluate the thermal efficiencies of the heating system in place. An ultrasonic based system was developed for this purpose over a standard industrial MODBUS protocol interfaced to the sensor node. The STUF-300EB flow meter from Shenitech [11] was used for this application. It provides excellent capabilities for accurate liquid flow measurement from outside of a pipe. Figure 4 shows the water flow readings obtained from running the meter for almost 4 days where flow activity can be clearly seen.

To monitor the water temperature passing in the heating pipes of buildings, a temperature sensor from SIEMENS [12] was selected for this application as non-intrusive units which can be mounted directly on a pipe inlet to sense the temperature of water passing through.

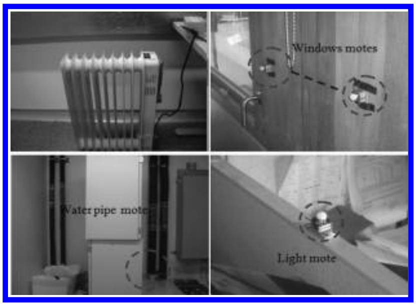

Figure 5. Number of deployment sites: on radiators, windows, lights and water pipe monitors.

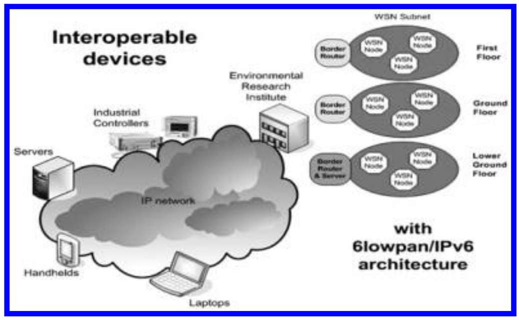

Figure 6. WSN in the broader view.

4 ACTUATION CAPABILITY

The wireless control of different types of AC loads in the building was incorporated into the network architecture in addition to its data collection capabilities in order to be proactive in the reduction of energy consumption in its deployment environment for which the building information models are being developed. Based on the data sets gathered in real time from the different types of sensors, commands are sent to some of designated nodes to perform actuation such as switching on/off the light, heat pumps, water valves or radiators. The sensor node design implemented provides two options to enable this actuation capability; the first for the control of small current devices, up to 2 Amps, e.g. a PC, using an on-board PHOTOMOS relay which is an opto-electronic device which drives a power MOSFET switch[13]. The second option provides the ability to connect an external relay that drives higher current loads through one of the on-board connectors.

To evaluate the actuation capability of the node and develop the necessary control algorithms, a demonstration was setup to control the operation of heater radiators as shown in Figure 5 based on selected data sets. The network monitored the room temperature/humidity and the appropriate command to the actuator to control the radiator autonomously.

5 WIRELESS SENSOR NETWORK ARCHITECTURE

The adopted WSN architecture is based on recently released IETF IPv6 over Low power WPAN (6 LoWPAN) (RFC 4944) open standard for IP communication over low-power radio devices—IEEE 802.15.4 represents one such link. WSN LoWPAN networks are connected to other IP networks through one or more border routers forwarding packets between different media including Ethernet, Wi-Fi or GPRS as shown in as shown in Figure 6 [14]. The IETF 6 LoWPAN standard extends the same communication capabilities to low-power devices whose battery power must last for months or even years. The 6 LoWPAN utilizes a pay-only-for-what-you-use header-compression scheme.

Through direct integration with IP routers, it can take advantage of advanced network security schemes rather than depending on those provided by ad hoc gateways. This implementation offers possibilities for widespread commercial adoption and broad interoperability due to its attributes such as openness, flexibility, scalability and manageability. Many industrial standards, including BACNet, LonTalk, CIP and SCADA, introduced an IP using either TCP/IP or UDP/IP over Ethernet.

6 DATA STORAGE AND REPRESENTATION

The Environmental Research Institute (ERI) building, located at University College Cork (UCC), Ireland was designed as a green flagship building and a low energy research facility [14]. Its building function includes a combination of both laboratory and office spaces requirements distributed in three floors. This building was chosen as the test bench for our large scale deployment because it is the most densely measured building on the UCC campus. However numerous required measurement streams are missing. When combined these reasons offer an ideal test bed for evaluation of scenario modelling using wired measurements and wireless measurements as obtained from a wireless sensor network.

To provide sensed data to the end user (or other software components) for the purpose of building performance monitoring (BPM), there are a number of conceptual and practical challenges that need to be overcome. The conceptual challenges can be the definition of BPM to different stakeholders of a building [15]. Practical challenges include data quality, availability and consistency, and benchmarking. A Data Warehouse (DW) implementation

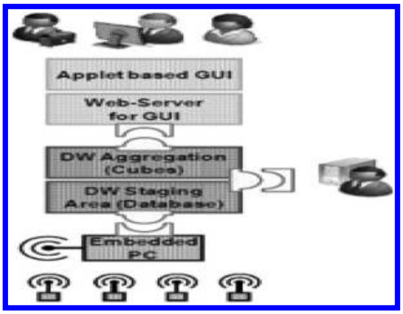

Figure 7. SOA for WSN to DW and DW to GUI.

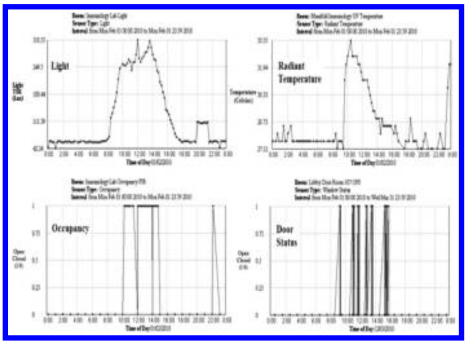

Figure 8. Sample of data recorded (a) lighting level, (b) radiant temperature, (C) occupancy and (D) Door status.

was created to store large data sets of data provided by the data streams of the WSN in ERI.

To extract the environment information from the WSN deployment in the ERI, a Service Orientated Architecture (SOA) was used [16].

For the ERI deployment, data is gathered from the first and ground floor and sent through the wireless backbone to an embedded PC (gateway) in the basement of the building. From the embedded PC, a SOA connection is maintained to a data warehouse (DW). Figure 7 shows the architecture used to gather data from the sensors and present data through a graphical user interface (GUI) to the end user.

A sample of the obtained results using a building operator GUI are displayed in Figure 8 showing one days data from lighting level (immunology lab), radiant temperature (immunology lab), door status (seminar room) and occupancy (seminar room), figure 5, In total (60) nodes were deployed in the selected three main zones within the ERI building to perform various functions of sensing and monitoring.

This building performance data is to be used to support decision making for facility managers and building operators to optimise maintenance activities and assist in fault detection and diagnosis, as defined, structured and stored in an integrated Building Information Model (BIM).

7 BUILDING INFORMATION MODEL BASED PERFORMANCE DEFINITION

One of the goals of this work is the development of a technology platform able to support holistic environmental and energy management in buildings [17] by leveraging cutting edge technologies and in particular formal performance frameworks. The methodology uses BIM technology [18] to define and store performance and their relative metrics associated to specific building geometry objects (e.g. building, floor, zone, wall …) or to specific HVAC system objects (e.g. pipe, air duct, pump, AHU …). All this information is stored in the BIM through the use of a tool named "Performance Framework Tool (PFT) [20]. The performances are structured in performance objects, objectives, metrics, aspects and scenarios (Figure 9).

A performance objective can be thought of as a qualitative objective that may be assigned to a particular performance object (building object). The easiest example of performance objective is "monitor" a parameter, but more complex performance objectives include qualifiers such as "maintain"; in this case a benchmark value has to be defined accordingly. For example, a building manager may wish to maintain the temperature within a particular range in a specific zone, within a building. This objective can be quantified by associating it with a performance metric, while the zone itself may be considered a performance object.

A building may have hundreds of performance objectives, so it makes sense to categorise them under particular performance aspects. In this way, similar performance objectives can be viewed together, in order to provide a clearer picture for the building manager. The five defined performance aspects are: building function, thermal loads, energy consumption, system performance and legislation. A scenario is a collection of associated performance objectives, concerned with a particular aspect of the building operation.

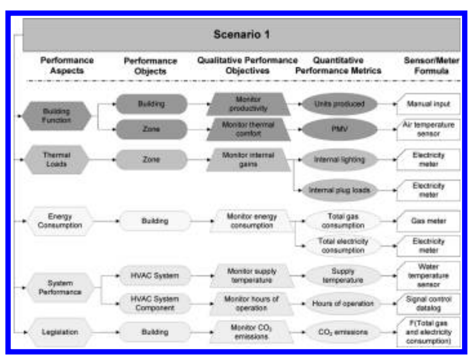

Figure 9. BIM based performance definition.

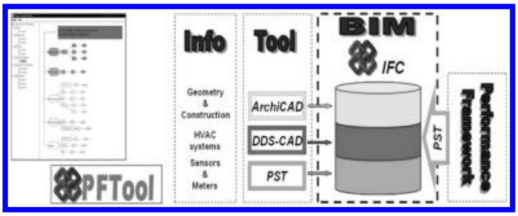

Figure 10. PFT Tool implementation.

Concerning the current technical implementation, using data harvested from the WSN system described above, the PFT tool (Figure 10), takes an Industry Foundation Class (IFC) file as its input, defines and appends scenario definitions, and exports the file in IFC format again. The output of this process is a formal description of the building and system measurement framework and the associated measured data required to monitor the prescribed performance. The measured data can be stored in a standard manually implemented data base or in an automatically implemented data warehouse that is IFC compatible. The data warehousing technology is a more powerful way to structure the data that allows the user to elaborate, pre-process and display them in different fashions [21].

8 CONCLUSIONS

This paper presents the design and development of a miniaturized WSN mote based on Zigbee technology for building monitoring, exploring its system control management and technology characters and its useage as an input tool in the development of Building Information Models (BIM). The Tyndall modular WSN prototyping tool was used to develop the appropriate WSN infrastructure for building monitoring, modelling and control to minimise energy consumption in the built environment.

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Towards a process warehouse based energy building information model

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ABSTRACT: This paper describes the realization of a Process Warehouse (PW) with associated business connotations into the Engineering domain. It describes the implementation of the Process Intelligence concept that systematically captures, automates, arranges and stores the analysis methods (collection, evaluation, representation) of building performance processes and data, into the Data Warehouse (DW) of the Energy Building Information Model (eBIM), developed by the Information Technology for Sustainable and Optimised Building Operation (ITOBO) project. The rationale for this realization is to improve the overall performance of the eBIM in real time, considering its corporate goals, load balance, scalability and higher availability of the Corporate DW (CDW) of buildings networks for the end users. The paper further examines the potentials of employing a distributed PW architecture into the ITOBO platform to improve its overall performance.

1 INTRODUCTION

A Data Warehouse (DW) integrates heterogeneous building performance data for building networks is also known as a corporate DW (Ahmed, et al. 2010) (CDW).

A DW that structures building performance data without automatically integrating the performance processes, i.e. follows the classical definition of Inmon (Inmon 1996) '*a DW is subject oriented, integrated, non-volatile, and time variant collection of data in support of management's decisions*', fails to support efficient engineering data processing and reaches the Process Warehouse (PW) (Kruczynski 2009, Vassiliadis, et al. 2001, Jarke, List and Köller 2000).

This necessitates employing a Process Intelligence (PI) concept into DWs, that systematically captures, automates, arranges and stores the analysis methods (collection, evaluation, representation) of building performance processes and data, with less programming (ARIS Process Performance Manager 4.1, Process Analysis Quick Start 2007, Scheer 1999).

Scheer (Scheer 1999) defined a PW as "*The result of systematically capturing, storing and maintaining business process know-how in a repository is called a process warehouse*".

A PW functions as a departmental DW and adopts the transformation of Inmon's definition of DW into business processes context as stated by Kannan (Kannan 2005) "*The process warehouse is a process-oriented, integrated, time-variant and non-volatile collection of data that helps management get a handle on its internal processes*".

1.1 *About the ITOBO platform*

ITOBO (ITOBO 2007) implements a web-based model named Energy Building Information Model (eBIM), which integrates a Building Management System with sensing, monitoring and IT tools to help facility management take decisive actions at short notice.

The architecture of the eBIM is shown in Figure 1. A DW, implemented in Oracle 11 g database engine, serves as a central repository. It provides services for the applications embedded into each component of the tool layer that support monitoring tools, intelligent control, diagnosis and maintenance tools, Data Mining (DM), decision support, and building energy simulation component. It further generates energy aggregations for all the building integrated into the eBIM.

1.2 *About DW technology*

Data is either regarded as fact or dimensional in a DW (Rob, Coronely and Crockett 2008). A Dimension is organized into a hierarchy composed of

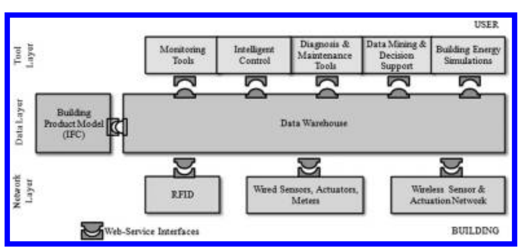

Figure 1. The ITOBO platform.

numerous levels, each representing details required for the desired analysis (Pedersen and Jensen 2001). Dimensions provide further context (descriptive) information to the facts allowing re-structuring (Adamson 2009). Fact data is associated with numeric measurements, for example, temperature, electricity, solar energy and CO_2 streams, and are stored in fact tables.

DWs provide data aggregation and pre-computing queries. The aggregation of the fact data are conceptualized in cubes. A cube conceptualizes data by assigning which dimensional data applies to what fact data and how the fact data is aggregated (Kimball and Caserta 2004). Cubes are automatically updated by encapsulating them in materialized views. A materialized view is a summary table of a pre-computed cube (Agrawal, et al. 1997) that provides efficient query execution and update capabilities (Oracle 2009).

2 PROCESSING BUILDING PERFORMANCE DATA WITH DW

In addition to the services in the tool layer (Figure 1) that the DW provides, the most common DW data operations apply to it. These include extraction, transformation, transfer, cleansing and computations.

To avoid excessive disk space and CPU usage of the CDW, buildings' performance data were loaded nightly. This gives historical information relevant to building performance that is at least one day old. For example, the monitoring tools component (Figure 1) collects occupants' feedback regarding their thermal comfort status. If the feedback is negative, no immediate action can be taken but action can be taken in both a short and long term basis.

The CDW of the eBIM, so far, contains over 25 million records of measurements (datasets) for the Environmental Research Institute (ERI) building. A process of integrating the Civil and Environmental Engineering (CEE) building in UCC, Ireland, and HSG Zander Hotel and Training Center in Frankfurt, Germany, is underway, with the possibility to integrate more buildings.

Additionally, with the possibility of integrating more buildings in the framework, more services are requested. Different processing scenarios are performed to meet the tools requirements with regard to data transformation, cleansing and finally computation. These vary in similarity to diversity. Currently, building performance processes and data preparations are performed separately on the server of the CDW. This can result in duplicated data in the CDW, extended processing time, and consequently reduction the overall performance of the eBIM. Tools that have similar data processes can be integrated into one step. Conflicting processes can save their results but not the raw data, as it is always available in the CDW. Also, in a distributed architecture of PWs, tools in one PW can benefit from the performance results of a different PW, i.e. utilizes the data transfer concept.

To give an in depth analysis of the idea and motivate the discussion, the following subsections illustrate some of the limitations in using the central CDW to perform building performance processes. It uses data aggregation, processing data for mining and Fault Detection and Diagnosis (FDD) as an example.

2.1 *Generating energy aggregations*

As taken from stakeholders' (Building owner, tenant, facility manager) requirements, energy aggregations (electricity, water, and gas) per building are provided by Online Analytical Processing (OLAP) based materialized views.

For each building in the framework, stakeholders require a full report for these aggregations, in one view, along the time dimension (aggregations per hour, day, week, month, quarter and year). Periodically these aggregations involve refreshing materialized views that affect the disk and memory usage.

As mentioned, data is loaded into the CDW nightly. This gives data aggregation one day behind, i.e. the hourly consumption of today is not included, which is a requirement. Including this into the views will increase the CPU usage, as the aggregation i.e. refreshing the views, will be computed almost at the request time. Achieving per hour aggregations of today will result in more requests to access these measurements, as a result of its availability and the need for closely monitoring energy consumption. This will increase the load and traffic on the server of the CDW and consequently decreases the response time, which results in poor performance considering the scalability and availability of the CDW.

Currently, the eBIM provides full reports in one materialized view (drill down). The drill down view, i.e. encapsulating all of the aggregation for each building in one materialized view, re-computes measurements that are not updated daily, such as energy consumption per week, month, quarter, and per year which is time and disk space consuming.

An aggregation is considered at the end of the specified period, e.g. per month aggregation is the accumulation of the records from the beginning to the end of the month. A comparison between the size and the refresh time needed to perform the drill down and per hour views is shown in Table 1. The generation of theses aggregations needs to be arranged for optimal performance.

Table 1. Time and size for individual and drill down views.

	Total time		Size	
Date	Drill down	Individual	Individual	Drill down
25-04-10	1,116.99	60.99	23,890	781,959
26-04-10	1,188.00	61.99	23,914	782,487
27-04-10	1,211.00	69.99	23,938	784,063
28-04-10	1,236.99	74.99	23,962	784,847
29-04-10	1,262.00	77.99	23,986	785,631
30-04-10	1,283.00	83.99	24,010	786,415
02-05-10	1,336.00	96.99	24,035	787,255
03-05-10	1,355.00	97.99	24,059	788,039

2.2 *Processing data for mining and FDD*

Currently, there are four mining models embedded into the DM and decision support, and a mathematical method in the FDD components in the tool layer of ITOBO framework. Two models, momentarily, provide occupants' thermal comfort state, and natural indoor illuminance levels in a room. A model periodically assesses a building performance against its day lighting design specification and a model to schedule rooms for future usage based on optimal energy consumption. The method in the FDD checks each sensor's reading and flags out of range readings based on the sensor's type and the specified ranges.

As mentioned, the data is loaded over night from the buildings' monitoring system. This gives a historical status of occupants' thermal comfort and all other performance measurements. Thus, there is no chance for an immediate action that can be taken to adjust for occupants' preferences.

Additionally, separately processing building performance data for each model in these components results on having duplicate copies in the CDW server of the same data. This wastes disk space and increases the CPU overhead.

The mining models use outside weather conditions and room sensors' measurements as part of their input. This involves similar data preparations, which are performed separately. In contrast to the FDD methods, this uses the same inputs but processes in a different way that requires data cleansing, while fault detection activities require accessing the data without modification. Outliers are used to detect faulty sensors that send readings out of range (e.g. sensor temperature in a room reads –70°C).

This can be overcome by systematically arranging the processes into levels so that each process provides the data for the next one e.g. having the FDD as part of the data mining outliers' detection process on the raw data before employing the cleansing and transformation. Also data can be prepared in a way that meets the requirement of all the models.

3 USE CASE SCENARIOS

The scenario is to perform data processing on an hourly basis in a sequence, i.e. a pre-specified order in a distributed architecture. These sequences were scheduled to start after the monitoring tools and building energy simulation components load their data into the CDW.

Each component stores data temporarily for processing and permanently stores the methods and the driven information (results). This raw data is always available in the central repository i.e. the CDW.

Processes were arranged in levels depending on the data processing scenarios that a performance process can be executed on the resulted data of a previous process. In a distributed implementation this could be performed in the same PW or access it from another one. Processes with almost similar data processes are to be stored into the same PW. The data preparation for these performance processes executed in a series that implements the pre-specified arrangement.

3.1 *Data aggregation scenario*

In a distributed implementation, this PW stores the building energy simulation component methods and energy aggregations results. The PW hourly collects information concerning systems functionality into designated tables into its server. It inserts this information into designated tables into the CDW server and deletes these records from the tables of the PW immediately after the insertion is completed.

This PW queries the DW fact table hourly, selecting the new added records of energy measurements, to provide current day hourly energy consumption, and temporarily loads it into its fact table. Then, automatically creates the hourly consumption aggregation (materialized views) in the PW server. When it finishes with the aggregations it appends the result to the previous view of the hourly table and drops the new added data from its fact table. The per-day aggregations are accumulated at midnight, by materializing the per-hour view into per-day, and append the new aggregations to the per-day view's table. At the end of this day, the PW automatically drops the new added data from its fact table.

The per-week aggregations are calculated based on the view of per-day. These views are the base for the per-month aggregations, which, in turn, are used to accumulate the per-quarter and finally the latest, are used to determine the per-years aggregations.

3.2 *Mining and FDD scenario*

This PW collects current weather and forecasting data from the monitoring tools component. This information is loaded hourly, temporarily into the fact tables of the PW for processing and permanently into the DW for maintaining historical records. The mining models in this PW use weather data as part of their input. The remaining input, which includes rooms' temperature measurement, is loaded from the fact table of the DW into the fact table of the PW.

The FDD mathematical method is employed first to detect faulty sensors, which is part of the outliers' detection process on running the mining models. The result from this process is saved to a relational table in the PW server. The raw data is loaded into the fact table of the DW with no cleansing.

The next step is to remove any outliers that were detected by the FDD method from the data set to score the mining models.

The thermal model is employed first to determine the occupants' thermal status in each room. This is followed by determining the natural indoor illuminance level and the room status with regards to the day-light design specification of the building, by employing the illuminance model. The results of these processes are saved to a relational table into the PW server. Finally, the scheduling model is employed using the weather forecasting data to identify low-energy comfortable rooms for future usage, as this model uses the output of the previous models.

The PW automatically drops the data that was loaded into its fact table after performing the FDD and mining operations, as this data has already been loaded to the fact table of the CDW.

4 IMPLEMENTING THE PWS

This section details the steps needed to populate the fact table of each PW and the performance processes.

The PWs will have the same architecture and design specifications as the CDW, but contain customized data and performance processes. The eBIM CDW contains four dimensions, namely time, location, organization, and measurement devices.

The common operational processes of pushing data into the PWs fact tables are the same as in the CDW that support the labor-intensive Extraction Transformations and Loading (ETL) operations. The relationship between the PWs and the CDW considering data extraction is taken care of in terms of SQL definitions.

Therefore, the extraction processes involves selecting specific new records from the CDW fact table and temporarily storing them into each PW fact table. Considering that the measurements are stored into one column 'value' of the CDW fact table, a 'select decode' PL/SQL function was executed to select new specific measurements from the CDW. This requires the existence of these measurements for a specific building, thus referential integrity constrains were employed to fulfill this requirement. For each measurement the 'measurement devices, and the 'location' dimensions primary keys (foreign keys in the CDW fact table) were used to select the required measurements associated with a building. The new records are specified by using the reading timestamp. A trigger checks, before any insert or update in the CDW fact table, the existence of new data from the buildings' monitoring systems. A database link was created to access the data in distributed PWs implementation.

The transformation, transfer, cleansing and computation processes vary depending on the application requirements in each PW. The following sub-sections give an overview of the measurement aggregation along with the monitoring tools and building energy simulation, FDD and mining PWs operational processes, for the purpose of illustration.

4.1 *Implementing the aggregations PW*

This section implements a distributed PW for measurement aggregation (electricity, water, and gas) per building along the time dimension, using individual materialized view for each measurement. It also serves as a temporary storage for users' feedback and the ideal building performance.

The fact table of the PW consists of the primary keys of the dimensions of the CDW table and three columns namely 'Electricity', 'Water', 'Gas' along with a column to store the reading timestamp. The PW contains two relational tables to store users' feedback and the specified ideal performance from the energy simulation component. These would guarantee integrating new buildings without altering the schemata of the CDW. The arranging of the processes in this PW is shown in Table 2.

4.2 *Implementing the mining and FDD PW*

The fact table of this PW consists of the primary keys, as these are on the aggregation PW's fact table, reading timestamp, along with the outside

Table 2. Sample of the operational process to create the hourly aggregation.

Activity	Expression
Select and Insert	Collects users' feedback and the specified ideal performance from the GUIs and inserts these values into the designated table in the CDW.
Empty the Relational Tables	Delete * from the relational tables.
Extract new energy raw measurements	Select decode (Meter Id, 'ERI0020109', value, null) Electricity, decode (Meter Id, 'HSG005000', value, null) Water, ...other measurement for electricity, water, and gas for all buildings From CDW Fact Table
Cleansing	Where exists (Select Building Name from Building Dimension where building ID = 'ERI' Union Where exists (Select the other buildings) Union Where exists (Select Device Id from Device Dimension where Device ID = 'ERI Electricity' Union Where exists (Select for the other buildings)
Computation	Create materialized view ERI Electricity Aggregation Compress ... other options As Select Decode (Grouping (To Char (Reading Time, ' HH24 DD-MON-YYY')), 1, ' All Hours' To Char (Reading Time, ' HH24 DD-MON-YYY')) Hour Of Day Sum(Electricity) Where Building Id = 'ERI' Group by Cube (To Char (Reading Time, ' HH24 DD-MON-YYY'))
Empty the fact table	Delete * from PW fact table

weather conditions (temperature, humidity, light level, total and diffuse radiation, wind speed and direction) for all the buildings, and a column for rooms' temperature.

A relational table to store the results of the mining activities consists of three columns i.e. thermal comfort status, illuminance and the scheduling labels along with the primary keys of the fact table was designed. Another table to store the faulty sensors, primary keys of the fact table was also created. The arrangement of these processes is shown in Table 3.

Table 3. Sample of the hourly processing for mining.

Activity	Expression	
Weather data collection and loading	Load the weather data for all the buildings from the web interfaces into the fact table of the PW and a designated table into the CDW.	
Cleansing	Same referential integrity checks as the step for the measurement aggregation.	
	Employ the FDD method to detect outliers and insert it into the designated table.	
	Remove the outliers from the newly added data as detected from the FDD method.	
Extract rooms' temperature	Select Reading timestamp, Decode(Device Id'D05485', Null) temperature room G01 ERI. Select the reset temperature for other rooms in the ERI, HSG, and CEE From the CDW fact table.	
Cleansing	Same referential integrity checks as the step for the measurement aggregation.	
	Employ the FDD method to detect outliers and insert it into the designated table.	
	Remove the outliers from the newly added data as detected from the FDD method.	
	Integrate outside weather conditions and rooms' temperature measurements.	
	Interpolates the measurements individually for each building to fill the null values.	
Transformation and computations	For the natural indoor illuminance model process	Score the model into the newly loaded data set then insert the predicted natural indoor illuminance into its column in the PW fact table.
		(Transform the predicted illuminance into 'enough' for values >500 LUX for offices and >150 LUX for labs, 'not enough' otherwise for all the rooms in each building).
		(This involves deploying the model into the outside light measurement along with each building's physical specifications).
	For the occupants' thermal model process	Score the model into the newly obtained data set, and then insert the predicted thermal class into its column in the PW fact table.
		(this involves deploying the model into the outside weather conditions and the rooms' temperature measurement along with each building's physical specifications).
	For the scheduling model	Add a column to store the scheduling class. (This requires calculating the scheduling class from the illuminance and comfort classes).
	Save the results	Select all from the PW fact table.
		Insert into the designated tables, the values above.
Empty the fact table		Delete all from the PW fact table

5 CONCLUSION AND DISCUSSION

A process intelligence concept was introduced that systematically captures, automates, arranges and stores the analysis methods (collection, evaluation, representation) of building performance processes and data into the DW of the ITOBO project to achieve the PW concept.

This allows adopting a distributed architecture to improve the availability and scalability of the corporate data warehouse and the processes embedded into the service oriented architecture of the framework. The improvement of the framework was carried out while keeping the cost of the hardware and software to a minimum.

The cost effectiveness of employing distributed PW is the flexibility of upgrading or adding software and hardware without modifying the framework. This also includes adding other interfaces or upgrading existing connections and plug-ins as they arise. PW software packages, such as Oracle, are improved on and upgraded as technology progresses. As packages such as these become more powerful so too does the hardware required to operate such software. This facilitates focusing the process specifications of the PW and the storage capacity of the CDW, in which disk space is critical. Thus, the PW can be upgraded or replaced as required for the applications embedded into it to ensure high processing capability. The CDW storage (repository) can be extended easily by adding new hard disk.

The cost of running and maintaining a high capacity processer machine, e.g. Oracle Exedata storage server, is much more than maintaining fast small machines. Additionally, the complexity and long learning curve of these super machines require specialist operators. For the facilities manager regular audits and upgrades are necessary to gain the optimum performance required to give the most relevant information in a timely manner. In an IT intelligent building this operation maybe monitored by an in-house IT technician. The prompt action in maintaining or improving operational and maintenance performance over a building life cycle should produce savings far in excess of the costs of updating or upgrading PW technology and its associated packages.

The work is progressing on the other components in the framework to develop methodologies and algorithms to meet stakeholders' requirements. On the finalization of these methodologies, the automation and implementation in their PW will be added to the remaining issues.

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Maintenance middleware for provision of building performance data

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ABSTRACT: With advances in mobile computing technology, building performance information can be more accessible to maintenance personnel to support more efficient decision making. Current Building Management Systems (BMS) support the control and automation building systems for heating, ventilation and lighting systems. Also, BMSs collect an abundance of performance data from its sensing infrastructure over time. This performance data can be provided to maintenance engineers to assist in inspection of faulty equipment. This paper describes a methodology for mobile maintenance services. It uses web-base technology to support the provision of building performance data to mobile users and assist in decision making of facility management (FM) stakeholders.

1 BUILDING MANAGEMENT SYSTEMS

With increasing integration of Information Technology (IT) and building heating, ventilation, and air-conditioning (HVAC) systems, many proprietary communication protocols have been developed to enable electronic processing of building performance data. This communication carries sensed data is used to support the automatic control and operations of individual components of HVAC systems (Capehart et al. 2008).

BMS systems function as software application and so require essential input and output data streams in order to interact with individual building elements (Jayamaha 2006). Inputs data are provided form sensing units in order to measure aspects of zones, with respect to temperature of heating and lighting conditions for occupants, and components like a gas boiler or a heat pump to generate hot water requirements. Output data is supplied to actuation units in order to control the operation levels and the distribution of heat and air throughout the whole building.

Over time BMS systems generate millions of readings and these are archived in custom forms for further analysis but require specialist engineering knowledge in order to diagnose faults (Levermore 1999, Stack et al. 2010). Using this sensed performance of system components and zones and the actuation commands sent to control components, we propose to extend the interpretation of data to support more effective maintenance activities.

This research is part of the ITOBO project which focuses on applying optimised maintenance procedures based on building performance levels and delve into aspects of building control (ITOBO 2008). Utilizing data warehousing methodologies on the flow of data from both the existing Building Management Systems and an additional Wireless Sensor Network deployment, a basis is provided to extract relevant aggregated building performance data for a maintenance system.

2 MAINTENANCE MIDDLEWARE

Maintenance activities include inspection, repair and replacement tasks in order to keep building operations up and running (Levitt 2002).

Maintenance software applications vary from asset management, inventory systems and scheduling tool for financial and coordination of FM resources. Also, mobile solutions are designed to facilitate the remote task management with little regard for information available from site BMS (Stack et al. 2010).

Middleware supports the communication and simplify complex, distributed applications. It includes web servers, application servers, and similar tools that support application development and delivery. In order to develop a bridge between the BMS domain and FM domain, a middleware for building performance services to support maintenance activities is required.

A middleware should support the following principles (Coulouris et al. 2001, Emmerich 2000):

- Fault-tolerance defines that if a single component in the system should breakdown then the system should still function.
- Heterogeneity outlines that the ability to enable communication between different hardware and software system.
- Openness entails the adaptability of the system to adjust to new functional requirements and new components can be easily integrated.
- Scalability classifies that the system performs as effectively as designed when increased usage occurs like large number of concurrent users should not degrade overall performance.
- Resources sharing enable distributed processing and utilization of software and hardware across the system.

An essential element to our middleware is the Service Oriented Architecture (SOA) paradigm. SOA is becoming de facto standard in the field of large software systems. It constitutes an innovative solution for integrating applications. It has been adopted to develop middleware for several years by many IT companies and research groups.

Core to defining processes and services to support interaction between the different parties in building management, is the identification of individual stakeholders (Wang et al. 2009). Fig. 1 describes the requirements of the various stakeholders were collected from industry partner involved in the development of building controllers, remote building monitoring systems, FM software developers and facility and energy managers. The roles identified were the facility manager for coordination of maintenance activities, the energy manager for energy conservation strategies, the building tenants as they occupy zones and their thermal comfort and safety must be maintained, the building owner who monitors overall costs and a building operator that performs maintenance work.

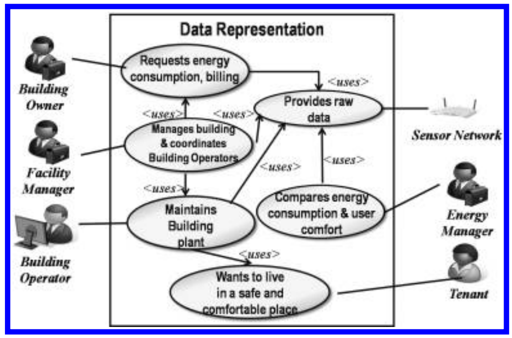

Figure 1. Stakeholder scenario for building monitoring.

Given the bounds required to produce a middleware solution a case study was performed on the Environmental Research Institute (ERI) which will be introduced next.

3 ENVIRONMENTAL RESEARCH INSTITUTE BUILDING

The ERI building, located at University College Cork (UCC), Ireland was designed as a green flagship building and a low energy research facility (Kennett 2005). Its building function includes a combination of both laboratory and office spaces requirements. The ERI building was designed as an ongoing experiment in green building design and operation with a particular emphasis on an increased knowledge of downstream performance. As a result, a state of the art BMS was installed to facilitate monitoring of the integrated hybrid heating and cooling system, building energy use and indoor environmental conditions.

This building was chosen because it is the most densely measured building on the UCC campus. However numerous required measurement streams are missing. When combined these reasons offer an ideal test bed for evaluation of scenario modelling using wired measurements and wireless measurements as obtained from a wireless sensor network (O'Donnell 2009).

3.1 *ERI Building Management System*

The six HVAC circuits are described in Fig. 2. The BMS functions with 210 sensors, meters and actuators. Sensing in zones is generally performed through air temperature sensors, while liquid temperature, flow and heat meters are required to ensure correct operation of building components. Overall electricity, gas and water consumption is also metered. For control, a number of valves can be adjusted for distribution of liquids and heat through the HVAC circuits.

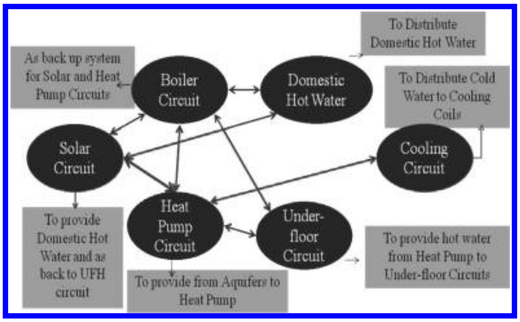

Figure 2. Stakeholder scenario for building monitoring.

Data from the BMS has been archived since February 2007 in a CSV (Comma Separated Value) form for further analysis. Over 21 million readings have been collected over a three year period, and readings are received at a rate of 15 minutes.

3.2 *ERI Wireless Sensor Network*

A Wireless Sensor Network (WSN) is also installed to complement missing measurements from BMS for a more complete building sensing infrastructure and research aspects of wireless sensing and actuation. The main objective of these sensors besides recording the building data is to make the mote reliable for large scale deployment with low cost and low power consumption.

The sensors were selected carefully to meet both the building monitoring and design requirements. Beside the sensing capability, actuation and interfacing to external meters/sensors are provided to perform different management control and data recording tasks. The experiments show that the developed mote works effectively in giving stable data acquisition and exhibits good communication and power performance.

Deployed sensor types include occupation sensors (Passive infrared PIR) for detecting occupancy of rooms, relative humidity for monitoring air quality, temperature, light, window/door status monitoring to check if they are open or closed, water flow and electricity meter interfacing for with various forms of pipes and water pipe/radiant temperature interfacing. For actuation, the wireless control of switching on/off different types of AC loads can be used on lights, heat pump, water valves or radiators (Jafer et al. 2010).

The adopted WSN architecture is based on recently released IETF IPv6 over Low power WPAN (6LoWPAN) (RFC 4944) open standard for IP communication over low-power radio devices—IEEE 802.15.4 represents one such link. The IETF 6LoWPAN standard extends the same communication capabilities to low-power devices whose battery power must last for months or even years.

The IP above offers widespread commercial adoption and broad interoperability due to its attributes such as openness, flexibility, scalability and manageability. Many industrial standards, including BACNet, LonTalk, CIP and SCADA, introduced an IP using either TCP/IP or UDP/IP over Ethernet (BACnet/IP, ODVA).

Collecting, storage, analyzing, processing and structure of this raw information needs to form the basis of the building performance and maintenance middleware.

4 MAINTENANCE SERVICE INTERFACES

For development of maintenance middleware, service interfaces need to be defined about the data requirements of the building management components. Fig. 3 presents an overview of the packages identified to support data collection, data storage and processing and end user interaction. For maintenance purposes, the key elements are Maintenance and Monitoring Tools, Data Warehouse and Sensor and Actuator Network.

Maintenance and Monitoring Tools are defined by end user requirements. They enable the user to interact with the system through presentation of building performance data and maintenance task information. These tools should provide timely and accurate information to assist user with the daily activities. Internal processes for providing data should be hidden and the information should be available on devices running different operating systems and hardware platforms.

Data Warehousing is a methodology to process bulk data from multiple data sources and produce custom views of the building performance data. Data collection from the sensor and actuator

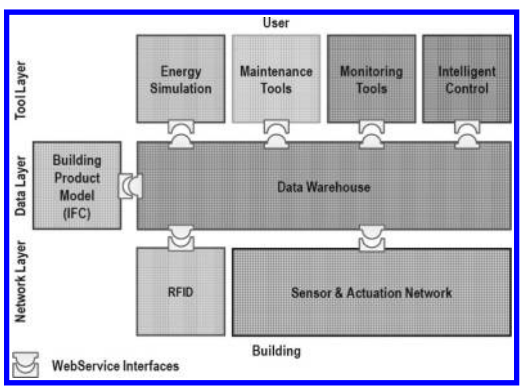

Figure 3. Middleware service interfaces to support component information exchange.

network must support various types of sensing and actuation devices. Having collected the readings, the data is associated with dimensional data which provides an association to the purpose of the sensing device. Using these properties, materialized views are formed to automate algorithms, averages and accumulations of building performance data. These resulting views supply the information required by the end user tools.

Sensor and Actuator Network supports to transmission to actuation devices and from sensing motes.

Having identified the basic requirements for inter-component communication, a prototypical deployment was performed.

5 MAINTENANCE MIDDLEWARE DEPLOYMENT

The development of the maintenance middleware was implemented using Web services. Web services are a standard method for implementing SOA platforms (Stack 2009). Fundamental to Web services is the definition of interfaces to enable communication and interaction between components. The initial steps involved the collection of data from the ERI BMS and WSN, and also actuation through WSN. Once the data is stored, data warehousing techniques are applied and services are supplied to the tool layer. Finally, the building stakeholders view a representation of building performance and maintenance data in the form of graphical user interfaces (GUI).

5.1 *BMS and WSN service interfaces*

In order to collect data from sensors and actuators a set of tables were designed to store reading information. A classification schema was required to store attributes of sensing devices and their purpose. Relevant information includes location, building equipment, input or output, the range of data sensed and the unit of the reading value.

BMS data is imported from CSV files on a daily basis. Most controllers in the BMS have a sensing interval of 15 minutes and imply that 96 readings should be collected per day. Currently, the WSN sensors send readings every 12 minutes. Once readings are parsed from BMS files or received from WSN, the Data Warehouse data collection service is instantiated, supplying a unique identifier of the sensing device, time of reading and value of the reading. Fig. 4 is a visual representation of the data received from a wireless radiant temperature sensor over a 24 hour period.

Also, a Web service interface was created to let other modules to access and control WSN

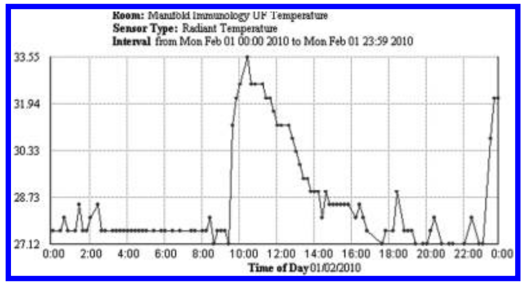

Figure 4. Reading data from radiant temperature monitoring an underfloor heating temperature of immunology lab in ERI.

actuators. For example, there is a function to turn on/off the actuator. The client provides actuator's address and it's operation level (0 to turn off actuator and 100 to turn on actuator), a confirmation result will be returned to show if it is successful or not.

Given that sensing and actuation devices are of different types, the middleware has heterogeneous properties and easily integrates new devices in the sensing layer.

5.2 *Data warehousing service interfaces for building performance*

Storage and processing using data warehouse techniques for the purposes of serving building performance and maintenance data to end user tools. Oracle 11 g Data Warehouse application was used to store the building performance data and associated attributes. Views of the data were created to easily access historical building data.

With traditional database systems, access times to data will decrease with more and more records being collected. The data warehouse views are calculated overnight and so enabling constant access times for end users. The resultant tables created as output of the views are access by the end user Web services.

Fig. 5 is a Web service interface created for a building operative. The methods outlined supply information about the maintenance tasks assigned to the engineer. Through the method get Equipment Performance History, aggregated performance data is supplied to the end user. Rather than showing live or historic sensors data that record information about inputs and outputs of a building component, actual performance levels of the component can be displayed. For example, the most recent operation of a Heat Pump could be graphically compared with optimal performance levels over a selected time interval.

As processing is performed in different components within the middleware, resource sharing

```
public interface BuildingOperative {

    public String login(int userID);

    public ArrayList getTaskDetails(int taskID);

    public ArrayList getAssignedTasks(int userID);

    public ArrayList getTaskClient (int taskID);

    public String getCatID (int taskID);

    public ArrayList getTaskResources(int taskID);

    public ArrayList getTaskIDS (int itemID);

    public ArrayList getEquipmentPerformanceHistory(int itemID);

    public ArrayList getEquipmentTaskHistory(int itemID);

    public boolean startTask(int taskID);

    public boolean completeTask(int taskID);

    public int getItemIDForTask (int taskID);

    public void printToScreen(String output);

}
```

Figure 5. Building operative web service interface.

is achieved. Fault tolerance is also supported as each component can continue to function independently.

5.3 *Mobile Tools for Maintenance and Occupant Feedback*

Access from mobile devices and desktop applications enables the stakeholders to interact with the system. Fig. 6 is a prototypical view to provide a Building Operator view of building performance data. The view is divided into logical sections for graphically visualizing the data, locations or zones in the site they maintain the sensors and actuators in that zone and date selection. The data presented in the graph represents the gas boiler curve on 1st May 2009. The Maintenance and Monitoring Tools access the Data Warehouse Web services and the data received is displayed in a cognitive format to the end user.

Fig. 7 is a view of a Monitoring Tool to interact with the tenant in a building. The objective is to collect users' preferences through feedback on their current environmental conditions. Based on analysis of the user responses, actuation commands can be initiated. For example, if the user is extremely cold and the system finds that the room heating conditions are below normal, then the service in the WSN is called to turn on the heater in the user's room.

Through our Web services implementation, a middleware was created to integrate various components to improve the provision of building information to end users and with improved data analysis techniques, it supports more accessible

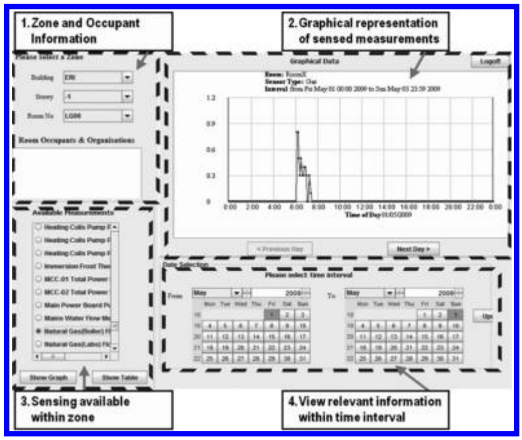

Figure 6. Graphical user interface for building operator.

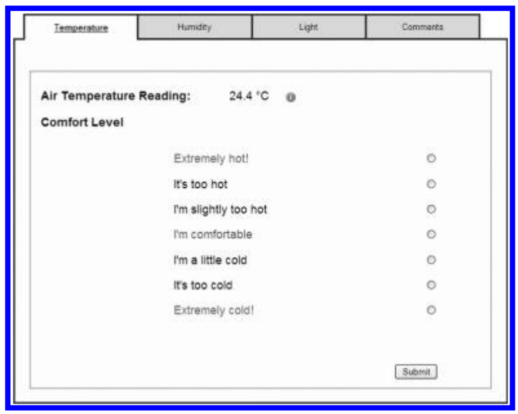

Figure 7. Thermal comfort feedback from tenant.

and easier understood information to support stakeholders' decision making processes.

6 CONCLUSION

Using BMS and the ERI WSN data, a service is for building performance and maintenance data to maintenance engineers using mobile tools. This middleware enables the collection of sensed data, processing and analyzing the data and preparing the data for representation to stakeholders.

Following the principle of middleware, the maintenance services provide a complete system for the support of maintenance personnel. Individual components interact seamlessly to form robust maintenance and monitoring tools. The use of resources for sensing, data storage and user interaction is highly scalable and enables many different types of software and hardware to interact.

7 FUTURE WORK

Further integration with maintenance scheduling processes is planned. This will incorporate the role of the facility manager to coordinate maintenance activities. Use of the building product model and Industry Foundation Classes (IFC) will provide a standard for exchange of data in the building domain. Interaction with current BMS communication protocols is in development.

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Information technology for optimised building operation

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A platform for the Optimisation of Building Operation

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ABSTRACT: This paper describes research achievements and future work of the Strategic Research Cluster ITOBO (Information Technology for Optimised Building Operation). The cluster is funded by Science Foundation Ireland and supported by five industry partners. Research addresses the development of an integrated, holistic ICT-platform to support the optimal operation of buildings from three different perspectives, the end user perspective, the operator's perspective and the owner's perspective. The work of the cluster is structured in three research strands. The first research strand focuses on the development of wireless sensing infrastructure, including the required protocols. The second research strand focuses on the acquisition, management, and analysis of Building Performance Data, and the third research strands focuses on the development of AI-tools for systems diagnostics, the modelling of user comfort and user behavior and maintenance planning and scheduling. This paper gives an overview about recent research achievements, evaluates these results and presents plans for future work in 2011 and 2012.

1 STATE-OF-THE-ART

1.1 *The challenge*

The construction sector and buildings' operation have been identified as major sources for energy consumption and CO_2-emmissions. As a result of the Kyoto Protocol Process many countries developed standards and regulations aiming to reduce the energy required to heat and cool buildings and to provide appropriate lighting in homes and workplaces. Furthermore, the usage of renewable energy sources has been stimulated and supported in many countries to reduce the carbon footprint of our built environment.

As a result of these actions buildings and building services systems are becoming more complex through the integration of multiple energy sources, energy storages, and complex monitoring, control, and actuation systems. Not just the technical interdependencies of the different systems and components but also the socio-technical interactions of users and operators with the different systems and components needs to be modeled, monitored, analysed, and controlled by advanced and fully integrated IT-systems.

The Strategic Research Cluster (SRC) ITOBO addresses these challenges by developing an integrated sensing platform, an integrated building performance management system, a model based diagnosis and comfort management toolset and maintenance management components.

1.2 *Building performance management*

The performance of buildings is usually specified in standards of professional bodies (ASHRAE 86147, 2007; VDI 3808, 2010). This is complemented by legislative regulation on Energy Ratings (SI 666, EnEV 2009, DIN18599 2009) and Sustainability Criteria (BREEAM, LEED 2009). The performance criteria are specified on different hierarchical levels, such as on building level, room level, BMS-component level, or on systems level.

Usually, two major engineering systems contribute to building performance, the "core and shell", designed and manufactured by civil engineers and "building services systems" designed and manufactured by mechanical and electrical engineers. For the operation and maintenance of these systems different business models exist ranging from "holistic scenarios"—such a Total Facilities Management—to fragmented models, such as in-house Facilities Management.

This fragmentation of disciplines led to the development of different, poorly integrated information models and data modelling standards. Components of the "Core & Shell" are usually designed and document with CAAD or CAD systems. The Industry Foundation Classes (IFC) and Green Building XML are two prominent and well known standards for the management and exchange of Building Information.

On the other hand many standards and protocols exist to model, document and control Building Management Systems. One prominent standard in the BMS-arena is BACnet—A Data Communication Protocol for Building Automation and Control Networks.

Last but not least the Facility Management sector has also developed numerous standards to describe and structure information required to specify and characterize building performance; examples are the regulations of the German Association for Facility Management [GEFMA 2010].

This fragmentation of sectors including the underpinning ICT-infrastructures is the major reason that a holistic, integrated description of building performance is not available and supported by commercial products today.

Most of the research achievements published focus on either the development of improved design support tools or the improvement of the operational phase. However, integrated approaches are rare.

1.3 *Wireless sensor platform*

Recently, commercial wireless sensor platforms have been released to the market. Examples for deployments are documented in the web [EnOcean 2010] and through literature [ITOBO D1-4]. The following section highlights the specifications of the two protocols used and deployed in ITOBO.

The standard IEEE 802.15.4 specifies the physical layer and medium access control for low cost, low power, low data rate, personal area wireless networks. It operates on one of the possible ISM bands (868 MHz, 915 MHz, or 2.4 GHz). Two types of network nodes are specified, Full Function Device (FFD) and Rreduced Function Device (RFD). Two operating modes, non-beacon and beacon enabled, are possible.

ZigBee is a low-cost low power, wireless mesh networking standard that defines the network and application layers to sit on top of IEEE 802.15.4. Among the main applications being targeted by the ZigBee-alliance is building automation. ZigBee offers two stack profiles (release 2007); a lightweight stack profile 1 which is aimed at home and light commercial applications whereas the stack profile 2 (ZigBee Pro) provides additional features such as multicasting, many-to-one routing and high security with Symmetric-Key key exchange. Both stacks provide full mesh networking.

The 6 LoWPAN standard has been specified by IETF in RFC 4944. It provides networking capabilities for IEEE 802.15.4 network devices and supports internet connectivity with IEEE 802.15.4 networks. The standard proposes an adaption layer to provide interoperability between IPv6 and 802.15.4 networks and provides support for mesh topologies, IP header compression unicast and multicast routing. The target application space for 6lowpan is low data rate applications, which require wireless internet connectivity.

Several wireless hardware modules are available on the market. Only a few of these proprietary platforms are customized for usage in the building industry.

TMote Sky is a 250 kbps, 2.4 GHz, IEEE 802.15.4 compliant radio device providing physical and some MAC functionality. It incorporates temperature, humidity, and light sensing capabilities with TinyOS support and an integrated onboard antenna with up to 50 m range indoors. The first generation of our ITOBO platform was based on the TMote platform.

Soekrisnet 4521 is an embedded computer for wireless communications based on a 133 MHz 486 class processor and supports power over Ethernet. It can be expanded with multiple card adapters and has been optimised for use as wireless router. ITOBO uses the Soekris components as FFD in its meshed networks.

Last but not least ITOBO uses SUNspot nodes based on ARM920T processor supporting J2ME technology which allows us to program in JAVA.

1.4 *Constrained based techniques*

There is a potential for a great deal of information being available to inform building control and maintenance decisions. In particular, from various sensors, from the users regarding their degree of comfort, from the BIM regarding technical parameters and building usage information, and data available from the use of building simulation.

However, this available information is seldom exploited in an integrated and holistic way for analysis and reasoning to better inform building operation and control activities.

Numerous works are targeted at identifying the preference of occupants [ASHRE 55, 2004] and [ISO/DIS 7730, 2005]. The standards are based on average criteria for population comfort under the guideline of the widely used Predictive Mean Vote

(PMV) and Predicted Percentage of Dissatisfied (PPD) indexes (Fanger, 1970).

The vast majority of approaches capable of learning individual user preferences are based on the assumption that each office is occupied by a single user only and that his comfort feedback can be acted upon straight away. In contrast, ITOBO intends to learn the comfort settings that maximize the overall satisfaction of multiple users sharing a single office. That has required ITOBO to develop strategies that can handle conflicting feedback of different users.

Moreover, ITOBO intends to find the best thermal comfort conditions for meeting rooms that are occupied by different groups of people where not only the people sharing the room at the same time might have conflicting preferences, but where also the overall preferences among groups might differ.

2 THE ITOBO APPROACH

2.1 *Building Performance Metrics*

The development of a Building Performance Metrics (BPM) delivers a formalized and well structured solution to describe the design intent of buildings. It addresses the identified need for a holistic and consistent modelling of performance parameters of different systems. The BPM allows specifying overall design goals as well as system and component specific performance criteria and links them to building components rooms, zones or whole buildings.

The development of the BPM is based on the Scenario Modelling Technique (SMT). This technique utilizes Performance Aspects, Performance Objects, Standardized Performance Objectives and Metrics and accounts for the established profile of Energy Managers.

The Performance Aspects (PeAs) illustrate the importance of Building Function, thermal loads, HVAC system performance, energy consumption and building performance with respect to legislation.

The Performance Objects (PeOb) describe elements of the Building Information Model (BIM) which contribute to deliver a dedicated building function on either Building Level, Zone Level, System Component Level, etc.

The Performance Objective and the Performance Metric are attributes or formulas linked to a Performance Object. They describe a facet of performance for a defined PeOb.

The BPM is based on the paradigm of Building Information Modelling (BIM). Work at NUI G builds on the development of the Industry Foundation Classes (IFC 2005) and uses the methodology of the Information Delivery Manuals (IDM) to describe data structures and sequences for information processing.

By linking the BPM with the Data Warehouse Platform ITOBO delivers a methodology that allows to compare design specification with current conditions of the individual categories of PeOb during the Operational Phase of buildings.

2.2 *The Data Warehouse Platform*

The Data Warehouse Platform is a key component of the ITOBO project. It ensures that building performance data can be stored and management in an integrated and consistent way.

A generic process for the Extraction Transformation and Loading of data from different sources was developed and implemented. We distinguish into

1. fact data; i.e. sensed and metered data compiled either from BMS or directly from wireless sensors and meters and
2. Dimensional data, i.e. data compiled from CAD-systems, ERP systems or other domain specific systems which are used to categorise, classify and aggregate fact data.

For the development of the data warehouse schema international standards were analysed and used for the specification of the information objects.

A stakeholder analysis was performed to identify the information needs of potential user groups and to specify the required algorithms for the generation of aggregated data. We have identified three major stakeholder groups (1) building users, (2) building operators, and (3) building owners.

Building Owners require densely aggregated information given them a total overview about building performance on building or campus level and allowing quick and easy understandable comparison of trends and major developments. We provide this information by modelling and implementing so called 'Materialized Views'.

Building Operators require near real-time information on the finest level of granularity. However, this information needs to be structured in different ways, e.g. per tenant, per location, per time, etc.

Building users require energy information in an easily understandable formulation per zone. In this case a minimum need for navigation should be required. The Data Warehouse platform can provide this information as sub-cubes structured exclusively for the dimension "location".

The Data Warehouse Platform represents a unique achievement of our work in ITOBO, since it supports the management of Building Performance Data in a logically consistent and access to

Building Performance Data in a performance optimised way. The major achievement is the development of the Data Warehouse schema.

2.3 *Data Warehouse Interfaces*

Building Performance Data compiled in the ITOBO Data Warehouse Platform is accessible through web interfaces; (a) web services using the SOA protocol providing access to Building Performance data for third party applications (Application Programming Interface) and (b) Java-based Graphical User Interfaces (GUI) providing direct access to Building Performance Data for users.

Web services are typically application programming interfaces (API) or web APIs that are accessed via Hypertext Transfer Protocol. They are executed on our remote Data Warehouse System which hosts the requested services.

ITOBO also provides GUIs allowing access to aggregated or raw data. Since these GUIs run against the Data Warehouse Platform users can also access aggregated, or otherwise pre-computed information in real-time. In ITOBO phase 1 the research effort was on identifying the different information needs and developing initial examples for multi-dimensional information representation. In some cases the GUIs contain interactive elements allowing the collection of feed-back from the user on how they perceive User Comfort.

2.4 *The ITOBO wireless sensor platform*

The ITOBO wireless sensor platform addresses the identified need for a robust, low-maintenance sensing and metering infrastructure. The Tyndall Gen2 motes feature minimal energy consumption for operation and optimised energy harvesting from miniaturized, commercially available off-the-Shelf Amorphous Silicon Solar Panel (For Indoor Applications), Hybrid Energy Storage with Super-capacitor and Lithium Polymer Thin Film Battery, Ultra-low Power Energy Management for Indoor Light Energy Harvesting, and a Self Start and Over Charge/ Discharge Protection Subsystem.

Furthermore, the Distributed beacon scheduling mechanisms for IEEE 802.15.4 beacon-enabled networks enables low power mesh networking operation mode. ITOBO has currently achieved 80% power reduction compared to non-beacon mode.

With these features the required mote power could be reduced from 400 uW to 120 uW. A continuous operation is possible based on 12 hours light available at 350 Lux. The mote can be operated for 58 hours in darkness (week end cycle).

2.5 *Assistance for wireless network design*

ITOBO provides the first tool to support indoor wireless embedded network design and deployment with automatic design elements. The demonstrator features on mapping of site specific requirements to optimisation criteria and an agent based optimisation. The design support tool provides the capability to evaluate the impact of changes in network infrastructure, to evaluate potential multi-hop routes based on Received Signal Strength Indication (RSSI) and to estimate the life time of the network based on user requirements.

The design support tool supports a two-step-approach; in step 1 sensors and actuators are placed in the model. In step 2 an automatic design of the required communication network to support data transfer is executed. It combines accurate propagation modelling with optimisation algorithms to optimize the number and the location of wireless devices.

The tool supports manual and automatic design functionalities. Manual design functions are (1) to evaluate network expansion and the viability of new applications, (2) to estimate life time of the network with the included battery model, (3) to consider environmental changes (e.g. wall added/ removed).

The optimisation output includes the number and position of devices, a topology visualisation and a deployment plan for system integrators. The optimisation output is mapped to floor plans and includes a 2D/3D visualisation of the RSSI prediction.

The Wireless Network Design methodology and the related toolset have been evaluated in multiple site surveys with an emphasis on tuning the propagation model in various environmental types.

2.6 *Preference reasoning for building control*

A major source of energy inefficiency in buildings is sub-optimal control. Lighting is one of the main energy consumers in buildings, responsible for 20% of energy usage in commercial buildings in the USA [EIA, 2003]. Up to 58% of this may be wasted due to inefficient lighting control (Delaney, D.T. et al. 2009).

Within ITOBO phase 1, as one of our approaches to lighting control optimisation, we developed a higher-level controller which periodically optimizes initial settings coupled with a lower-level controller which actuates the lights. ITOBO formulates the higher level problem as constraint based optimisation. The ITOBO system assumes that a tracking system can monitor the location of individual users in the controlled zone and the availability of an interface which allows users to express preferences over the lighting scene. When significant changes occur in the environment, the constraint optimizer computes initial actuator settings which minimize an objective function combining user preferences and energy consumption. The reactive controller then maintains the desired luminance levels by actuating natural and artificial lighting devices.

The optimizing controller is responsible for computing on request settings for the actuators which optimize both energy consumption and user satisfaction. We model the energy cost and the effect on the building environment of the actuators, and the preferences of the occupants as a Constraint Problem.

We model each occupant's preferences as a preference curve which associates a satisfaction level of 0 to 1 with each possible lux level. These satisfaction levels may be derived from direct occupant feedback or learned over time based on their actions with regard to the lighting. By constraining the occupant's satisfaction to be above a certain threshold, we compute a range of luminance values within which the occupant is simply considered satisfied, and thus within which the energy cost component of the objective function will be the deciding factor.

To apply these preferences to the physical environment, we break it down into control zones, each of which contains a set of zero or more occupants. By averaging the preference curves of the relevant set of occupants, we produce a zone preference curve, which describes the overall satisfaction of that set of occupants.

Simulations show that the described ITOBO constrained based optimizer and control strategy for an intelligent, automated lighting system could contribute to up to 30% compared to a standard base line approach while maintaining occupant satisfaction at high levels. We have deployed a simpler version, with limited occupant feedback, in the National Demonstrator (see Chapter 3), achieving demonstrated savings of 40% of the lighting costs."

2.7 *Maintenance scheduling*

The impacts of troubleshooting and the elimination of failures and malfunctions of components of Building Management Systems on the daily business should be minimized in the best possible way. On the other hand, required replacements, repairs and other maintenance work should be not unnecessarily delayed to avoid degradation of other systems and components and increasing operational costs. Therefore, another research group in ITOBO focuses on the development of constrained-based optimisation of maintenance procedures.

Recent work in ITOBO focused on (1) Modelling of maintenance task processes, service company competencies, and collaborative workflows; (2) the design and implementation of constraint-based automated maintenance scheduler incorporating cost, energy and occupant needs, and (3) the development of global constraint for generalised multiple-resource cost-based scheduling.

Initial work focused on automated scheduling using fully-featured models requiring no user interaction. The objective is to increase the speed of solving and achieving optimality. The scheduling model constructed includes tasks with expected durations, required skills, deadlines and late penalties, inter-task constraints (precedence, concurrency, not-together), energy consumption data for delaying tasks, occupant time-window preferences, multiple engineers with skills, availability and overtime cost.

By applying new heuristics based on minimizing regret over not selecting a task immediately we could perform a constraint optimisation searching for the globally optimal schedule with problems of 120 tasks over a 1 week time frame, in less than 2 seconds in a first development step. By developing a new global constraint for scheduling over multiple *disjunctive resources* with optional tasks the constraint allows us to increase the problem size to 240 tasks and still generate solutions in less than 20 seconds.

2.8 *Competency modelling*

Work on maintenance scheduling is complemented by work on modelling the competencies of maintenance service providers in collaborative work scenarios. For this work we use ARIS as a Business Process Modelling Tool. The ARIS methodology allows us to describe "Activity Blocks" for relevant maintenance activities for dedicated components of building services systems and components. A more detailed description of this work is delivered in [Menzel et al. 2009].

3 ITOBO LIVING LABORATORIES

ITOBO addresses the complete R&D value chain. The cluster operates four Living Laboratories to demonstrate research achievements in real world scenarios, to test the feasibility of achievements and to prove the capability for 'large scale deployments'.

The living laboratories represent different types of buildings, technical systems, usage scenarios, and maintenance models. Table 1 below gives an overview about the yearly builds, the use case, and the major systems characteristics of the ITOBO living laboratories.

Table 1. Overview living laboratories SRC ITOBO.

	ERI	CEE	National Demonstrator	International Demonstrator
After 2005	•			
2005–1986			•	
1985–1936				•
1935 -> and older		•		
Offices/ public	•	•		
Laboratories/ public	•			
Industry			•	
Hotel/ leisure				•
Natural ventilation	•	•		
Mechanical ventilation	•			
Air conditioning			•	•
Low temperature heating	•			
District heating		•		
Gas mains	•		•	•
Electricity mains	•	•	•	•

3.1 *The ERI-Building*

The building of the Environmental Research Institute (ERI) at University College Cork (UCC) is a three storey building with approx. 2,500 m^2. It was inaugurated in 2006. The building is a concrete structure with high-performance glazing façade elements to the South. The building is equipped with a solar-thermal system to provide the required hot water for the laboratories and an open loop, geothermal heat pump system to provide the hot water for the low-temperature under floor heating. The renewable systems are backed up by a conventional gas boiler.

The building has been originally equipped with a wired Building Management System manufactured by CYLON (one of ITOBO's industry partners) consisting of approx. 180 sensors, meters and actuators. Four zones have been identified for intense monitoring:

a. an Open Office Space (South Facing)
b. the Immunology Laboratory (North Facing)
c. the Main Meeting Room including an Exhibition Area (south-East Facing)
d. an Office Space (North facing).

Table 2. Characteristics ERI-Demonstrator.

Demonstration areas	User awareness, User preference modelling Diagnosis, Maintenance Mgmt. Network design & RF-specification
Target systems	Low temperature heating system Natural ventilation Solar thermal and Geothermal systems
Installed components	Tyndall Motes (Gen 2) Wireless Protocol (IPv6) Data Warehouse Platform & GUI Data Mining Preference modeler

In order to achieve intense monitoring of thermal comfort and user behavior an additional 60 wireless sensors and sub-meters have been installed in these four experimental zones since Summer 2009.

Since 2008 a total of approximately 20 million data sets has been compiled in our Data Warehouse platform (by January 2010). This data is accessible to end users, operators and owners through the web-interfaces described above.

Furthermore, we have collected feedback about user comfort in one zone over a period of approx. 3 months.

3.2 *The CEE-Building*

The building of the Department of Civil and Environmental Engineering located on the Main Campus of University College Cork (short CEE-Building) is a three storey, brick built structure. The building is equipped with single glazed windows, a single pipe hot water central heating system and natural ventilation through dampers located underneath the operable windows.

ITOBO researchers in cooperation with researchers of the "Carbon Neutral Building Renovation Project" developed a BIM and an Energy Simulation model to advise UCC's office of Buildings and Estates about potential energy savings from renovation and upgrade.

Commencing in Summer 2009 the insulation of the roof, the heating control systems and the lighting system were substantially upgraded. Furthermore, the Computer Laboratories and the Drawing Offices were equipped with a heat recovery system which distributes the heat gains from the Computer Laboratories into the Drawing Offices.

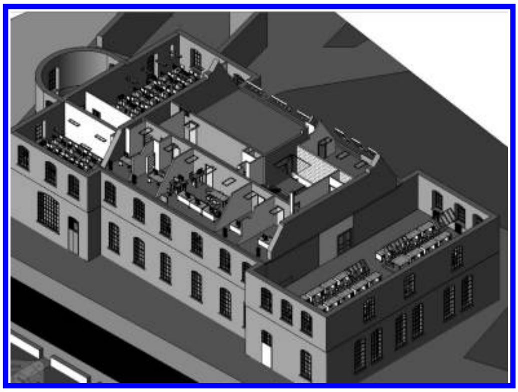

Figure 1. Peal-away drawing of CEE-Building.

Table 3. Characteristics CEE-Demonstrator.

Demonstration areas	User Awareness, Systems Operation and Calibration, Maintenance management, (Renovation Strategies*)
Target systems	Heating system Natural ventilation Heat Recovery System
Installed components	Data Warehouse Platform & GUI Data Mining Maintenance management system

Commencing in December 2009 the new sensor controlled lighting system and the wireless heating control system became operational.

3.3 *National Demonstrator—Industrial Facility*

The ITOBO National Demonstrator is hosted in the facilities of CYLON in Dublin, Ireland—one of ITOBO's industry partners. The building is an industrial facility with offices, meeting rooms and areas for storage and manufacturing. The building is equipped was a gas-fired heating systems and fluorescent lights. One of the major obstacles for energy-efficient operation was the inflexible lighting control.

3.4 *International Demonstrator—Hotel Training Center Frankfurt, Germany*

The ITOBO International Demonstrator is hosted by HSGzander in Frankfurt, Neu Isenburg, Germany. The building is a Hotel-Training Centre facility located in close proximity to the Frankfurt International Airport. The building is a concrete building with triple glazed windows. The complex hosts a kitchen, a restaurant, seminar rooms, leisure facilities (sauna, pool, bowling) and a hotel. It was inaugurated in the early 1980s.

Table 4. Characteristics ITOBO National Demonstrator.

Demonstration areas	Optimisation control algorithms (lighting and Heating)
Target systems	Lighting system Heating system
Installed components	Lighting control algorithms (using CYLON platform)

Table 5. Characteristics ITOBO International Demonstrator.

Demonstration areas	User Awareness, User Preference Modelling Diagnosis, Maintenance Mgmt. Network design & RF-specification
Target systems	Low temperature heating system Natural Ventilation Solar Thermal and Geothermal Systems
Installed components	Tyndall Motes (Gen 2) Wireless Protocol (IPv6) Data Warehouse Platform & GUI Data Mining Preference Modeler

4 ITOBO—FUTURE WORK

From 2008 to 2010 ITOBO researchers have focused on the development of a holistic, integrated hardware-software platform for Optimised Building Operation [Menzel et al. 2010], the development of novel algorithms, information models, methodologies for building performance specifications and diagnosis, and a holistic toolset for collaborative maintenance management and scheduling.

We have analysed the state-of-the-art in our research pillars and we have identified the deficits and shortcomings of ongoing research, including our own work.

For future work in 2011/2012 we have identified the following goals:

1. to consolidate our Living Laboratories and increase the complexity of test scenarios,
2. to concentrate on the development of reduced order models. This work aims to improve the understandability of complex system models and to improve the robustness, flexibility, and interoperability of implemented simulation, control, and diagnostics software.

4.1 *Wireless sensing infrastructure*

We will continue to focus on improving the capability for autonomous operation of the Wireless Sensor and Actuator Network (WSAN) infrastructure. Key challenges will be addressed in the following areas:

- Wireless Sensor & Actuator Mote Platforms,
- Self Adaptive Wireless Networking Infrastructure,
- Design, Deployment and Commissioning Methodologies for WSAN Infrastructure

Our key objectives in 2011/2012 are as follows:

- optimise power consumption of wireless sensor nodes with energy harvesting and associated power management to enable self-powered nodes with infinite lifetime,
- deliver a mote platform that enables actuation and control to be integrated at system level,
- achieve robust hardware packaging solutions based on a planar smart card form factor,
- create an embedded network management capability for WSAN to improve reliability, availability, and correct operation of the wireless infrastructure in building management applications, and
- integrate the WSN design tool with embedded middleware (WP4) and management capability to simplify infrastructure commissioning.

4.2 *Constraint based optimisation*

Future activities will be focused on the development of a strategy for zone-based, decentralised, mixed-initiative configuration policies which must be in sync with an optimised Building Operation Policy. This includes the development of a framework for overall building configuration policies, the development of a constraint-based framework to synchronize the different optimisation goals on a user-level, zone level and the overall building level, and the development of the control and diagnosis algorithms.

4.3 *Management and service architectures*

The overall objective is (1) to develop a set of system-level models that can be used as the basis for embedding building operations code for lighting and HVAC applications, (2) to decentralise the control, monitoring, diagnosis and reconfiguration code to the individual nodes in the sensor network, and (3) to co-develop the WSAN software and network infrastructure and hardware platforms that can host the embedded code. This work will focus on the following issues:

1. The further development of a decentralised approach for controlling lighting and HVAC that optimises user comfort while reducing energy consumption.
2. The co-development of a middleware framework for integrating the higher-level applications with the WSAN.

4.4 *Energy and facility management services*

The overall goals for future work in the area of Energy and Facility Management are (1) to expand the capabilities for integrated analysis of building performance data and (2) to provide support for adhoc maintenance and inspection management. This includes (3) the integration of mobile support tools into the overall system environment.

In terms of data management we will provide features to manage (1) the performance history of wireless motes, (2) the zone-based history of user preferences, and (3) the operational history of building services systems. We will extend the functionality of our mobile support tools to allow context-sensitive access to performance data, to enable the documentation of maintenance activities, and access selected diagnosis algorithms in the field. We will integrate our Maintenance Process Models into the definition of the Building Operation Policies.

Finally, we will work on mixed-initiative scheduling to allow real-time scheduling of additional tasks and develop a multi-agent software architecture to support dynamic maintenance task allocation amongst maintenance crews.

5 CONCLUSIONS & ACKNOWLEDGEMENTS

This paper presents research achievements (2008 to 2010) and future plans (2011/2012) in the area of ICT for Optimised Building Operation of the Strategic Research Cluster ITOBO.

Based on an intense state-of-the-art analysis research focused on the development of an Integrated Platform Architecture [Menzel 2010b]. This Reference Architecture has been used by the individual research groups to inform and guide the development of their individual contributions to the overall ITOBO platform, such as:

i. a wireless sensor platform with indefinite lifetime,
ii. a tool and underpinning methodology to support the design of indoor wireless sensor/actuator networks,
iii. a constrained based optimisation for lighting control,

iv. a constrained based maintenance scheduling tool,
v. a Data Warehouse Platform for Performance data management including the relevant middleware and GUI to access data and information,
vi. a Building Performance Specification tool.

In real world demonstrations ITOBO could prove that energy savings of up to 9% are achievable through the installation of new control algorithms, energy savings of up to 22% can be achieved through the combined installation of insulation, wireless heating and lighting control.

In future work ITOBO wishes to contribute to further efficiency gains through optimised, integrated control of lighting and HVAC systems and the optimised planning and scheduling of maintenance and repair activities.

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From performance specification to performance monitoring

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ABSTRACT: The building Facility and Energy Management (FEM) domain exhibits inefficiencies in the availability of consistent and complete building performance data. Conventional data storage solutions are insufficiently integrated with data management and analysis tools. Hence, their capabilities to contribute to an improved level of building performance are limited. In this paper, we outline the need to consolidate knowledge gains from construction and utilise these to specify performance metrics objects. The performance objectives have to be monitored in order to deliver consistently satisfactory building artefact in terms of comfort and energy consumption. Also introduced here is a methodology for data collection and consolidation for performance continuous commissioning.

1 INTRODUCTION

Article 229 in the Code of Hammurabi (Andrea & Overfield 2000) reads: "*The builder has built a house for a man and his work is not strong: if the house he has built falls in and kills a householder, that builder shall be slain*."

This is a performance specification statement and constitutes what are today called performance codes and regulations. The performance concept, when applied to a system, is concerned with outputs and often does not concern itself with the process of getting the outputs. In Buildings, performance is actualised through a set specifications, performance codes or regulations, and performance standards.

However there appears to be a disconnection between the standards, performance criteria and verification methods referenced by regulations and the qualitative performance or functional objectives found within the regulations (Meacham et al. 2005). More specifically, standards, performance criteria and verification methods often times have requirements that do not match the objectives of the performance (functional or objective-based) regulations. Also, there continues to be a heavy dependence upon prescriptive solutions as a comparative tool when undertaking performance design (Keller et al. 2008). This reliance occurs primarily because it has been difficult to quantify the existing prescriptive methods and in many areas there is a lack of technological advancement.

The inflexibility in regulations and standards stifle innovation and the Maxim "Customer is always right" does not apply to buildings. Prescriptive and deemed-to-satisfy codes focus on the technical solution to a problem which may never have been properly defined or understood (Soebarto & Williamson 2001). They have the advantage of simplicity, which makes them easy for architects, contractors and others to use. But they also create serious barriers to innovation, optimising costs, and trade. By changing the focus from the input materials specifications to the performance based measurements we will increase both the quality and the long-term value for money of our buildings.

It is apparent that in such approaches each individual building is a prototype and no lessons learnt from previous projects easily apply to the next project. Contractors who are often excluded from the specification and design of the buildings only concern themselves with material specification and consenting procedures. To achieve knowledge transfer, satisfy user requirements, it is necessary to outline specific performance criteria and monitor this asset. Asset monitoring provides feedback for qualitative and quantitative assessment of the actual performance.

This paper addresses the need for performance monitoring to achieve performance objectives and metrics specified at construction. It outlines the methodology for specifying performance criteria, monitoring the performance and delivering a satisfactory facility.

2 BUILDING PERFORMANCE SPECIFICATION

Meeting Buildings' performance objectives is a sustained effort from inception and planning, through commissioning to operation and maintenance. Building performance specification must satisfy the following:-

- The satisfaction of user needs in housing.
- Innovation in housing by providing a systematic framework for evaluation and acceptance.
- Communication among all housing stakeholders in order to achieve rational choice of housing and housing products.
- International trade in housing systems and housing products by replacing prescriptive standards that may serve as restraints.

Building owners, occupants and managers can easily understand affect building performance through standardised performance objectives and metrics. Each building is unique and consequently has an associated building specific set of performance objectives and metrics. To accommodate variation between buildings an ideal set of performance objectives and metrics (which is capable to describe the performance of any building) must be initially developed.

In order to make decisions all professionals across the building life cycle, especially the Managers and operators, need to be able to predict and assess the performance of their ideas with respect to various criteria such as alternative designs, comfort, aesthetics, energy, environmental impact and economics. Building performance analysis makes it possible to develop a methodology for scheduled operation and maintenance and to support other facility management functions (Jones & Sharp 2007). The building performance analysis can take the form of physics based models or data driven modelling. These are only possible if the performance metrics and objectives are embedded and associated with building intent and current performance information.

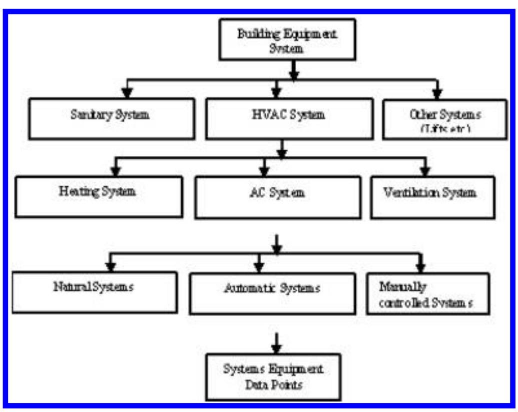

Figure 1. Building system breakdown as functional elements.

Taking a systems approach, building performance metrics and objectives are specified for whole systems (a building or a set of buildings). This system has active objects that constitute the process of achieving the set performance targets. The individual objects are as identified in, Figure 1 with the lowest level at the data extraction level. Each individual building component or object (walls, doors, heating system, solar panels) delivers certain measurable performance expectation against which it can be monitored.

3 BUILDING PERFORMANCE ANALYSIS

To achieve integrated, holistic and truly total Building Solutions that optimize energy usage, stores and inventory, maintenance planning, space scheduling and human resource task allocation, it is necessary to collect and maintain up-to date data on buildings and facilities in general. Current data collection and analysis tools are deficient in collecting data, generating tangible information and providing decision support for Facility Management (FM) (Fuhr et al. 1992).

With the introduction of non traditional energy systems, new competences are required for operation and maintenance. Virtual networks in collaborative scenarios can be designed to support these scenarios. If design and construction intent is clearly documented, captured into the product and process models, this can be compared with actual performance using simulation and monitoring results.

In the Information and Communication Technology for Sustainableand Optimised Building Operation (ITOBO) project (Stack et al. 2009), a methodology is defined that enables performance measurements to be compared with building intent. The ITOBO methodology outlines the following main areas:

- Translating the building intent into measurable performance metrics
- Building an operation and Maintenance Management System (MMS)
- Build a data warehousing specification and implementation that addresses the needs of all stakeholders
- Build user service components that are context sensitive for Decision support to all stakeholders (Menzel et al. 2004).
- Integrating the disparate information tools into a single BIM.

This methodology is what is outlined in the ITOBO architecture in Figure 2. To access actionable information, it is necessary to create a "self reporting building" with sensing systems of finer

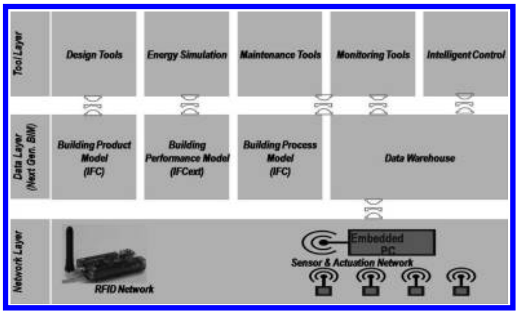

Figure 2. The ITOBO BIM model architecture highlighting the main layers and the attendant tools used.

granularity. This is achieved by using wired and wireless sensor, RFID and actuator Networks. The sensing provides spatially distributed information at much lower resolution that the current metering system. This sensor network, in the context of the ITOBO project is described elsewhere and the emphasis of this paper are the areas outlined above.

The data layer includes product and process models with editors allowing for exchange of data with the data warehouse. The data warehouse collects and integrates data from sensing and actuation. It also stores fault and maintenance information and aggregates it to support decision making. Decision supporting tools extract and process information from the tool layer. The different layers of this architecture are joined together by a web of published web services.

4 PERFORMANCE ANALYSIS FOR SPECIFICATION

To guide future designs and construction it is necessary to maintain an accessible knowledge base. The knowledge base must be supported by expertise from construction and consultancy to deliver new and innovative buildings of the future. Performance analysis for specification refers to process of obtaining design intent and using it to specify performance objectives and metrics. The objectives and metrics are then verified by using monitoring information. Here described is the performance specification with monitoring and feedback. Monitoring data is stored in a data warehouse.

4.1 *Performance specification*

In order to specify building performance and use these specifications in operation and maintenance, it is necessary to proceed through the following process:

- Define optimal building/system operation strategies according to accepted industry standards (e.g. ASHRAE, CIBSE etc.);
- Transform strategies into "performance scenarios" according to a formal methodology (Keller et al. 2008);
- Capture and migrate "performance scenarios" from building/system design to commissioning and operation;
- Utilise a standardised data model (IFC) to define and integrate the "performance scenarios" with geometric and HVAC IFC definitions realised through existing IFC compliant industry standard tools;
- Extend the standardised data model (IFC, MVD) to include a "sensor" reference model (IFC) to measured/simulated data.

The "Performance Specification Tool" defines and captures building operation strategies in terms of performance scenarios utilising Building Information Model (BIM) concepts & technology. These performance scenarios and their related metrics, are associated to specific building geometry objects (e.g. building, floor, zone, wall …) or to specific HVAC system objects (e.g. pipe, air duct, pump, AHU …).

4.2 *Monitoring building performance*

In the ITOBO architecture, monitoring Clients 'trigger' requests through the maintenance management system. For example, the client requests the optimised Temperature in Zones 1–5 on Floor 2 and associated Energy Consumption over a specified time period. The Performance Specification and Energy Simulation are activated through the Data Warehouse Part to clearly identify all of the necessary ITOBO Performance Framework Aspects/Objects/Objectives/Metrics that are needed to process the Monitoring request. This will involve identifying the appropriate Geometric Spaces (Building -> Floor -> Zone) and their associated attributes (Temperature & Energy Consumption). Each of these attributes will have associated relationships throughout the performance framework (Aspect -> Object -> Objectives -> Metric) finally resulting in a request for the appropriate data in time and resolution.

4.3 *Maintenance management system*

Maintenance actions are derived from (a) regular maintenance requirements and processes, (b) user reports and (c) building performance data and diagnosis. The actions are scheduled to optimise energy efficiency, cost and user satisfaction, while respecting constraints and preferences over resources, engineer availability, and building use. The schedule are updated continuously as tasks are completed, as engineers report their locations, and as new tasks are generated. Particular attention is paid to the roles of multiple service teams, requiring negotiation of contracts and service levels, and coordination of activities between the teams (Menzel et al. 2009). Relevant technical documentation and work orders are compiled. Information are forwarded in a context sensitive way to the individual maintenance clients.

4.4 *Data warehousing*

A DW is designed to support data analysis. It contains historical data derived from transaction data. It separates the analysis workload from the transaction workload. This helps to maintain historical records and enhance the understanding of the business processes. A DW environment includes an *extraction, transformation, and loading* component (ETL), an *online analytical processing* (OLAP), *engine* and *client analysis* tools.

The ITOBO data warehouse structures buildings performance data in order to meet buildings stakeholders' requirements (Figure 3). It enables fault detection and intelligent control, diagnosis and maintenance scheduling, while importing the specified ideal performance from the Building Product Model (BPM). This data warehouse integrates different data sources including the network and tool layer (wired, wireless sensor and RFID), user profiles, and facilitates loading building physical specification from the Building Information Model (BIM).

By defining the data requirements, the scenarios outline the expectations for data warehouse schema. Some typical examples of data warehouse schema description are outlined here.

4.4.1 *Building location*

Location is the logical subdivision of building spaces that interrelates users (occupants and operators), comfort requirements and the HVAC

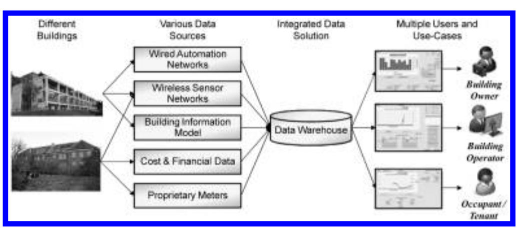

Figure 3. Integration of various data sources in DW (*adopted from Ahmed et al 2010*).

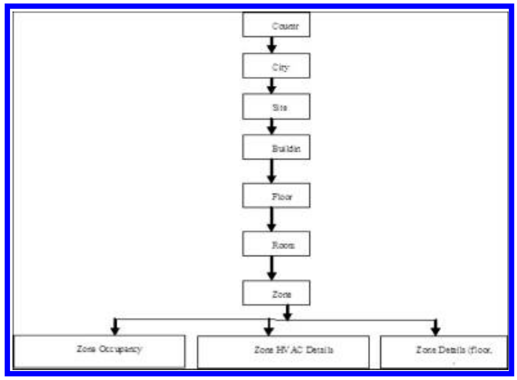

Figure 4. The location details pertaining to multiple buildings managed by a FM.

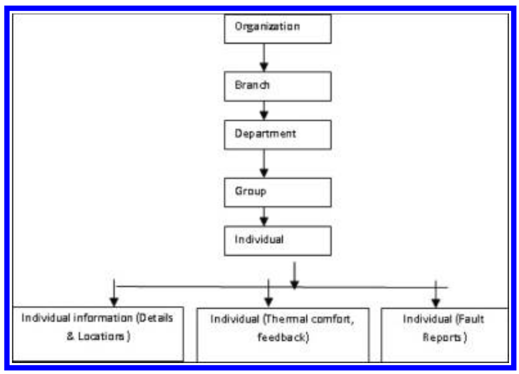

Figure 5. Organisation hierarchy identifying the main data sources.

or lighting zones and supporting the working environment. Location is used by facility managers in planning and scheduling as well as in facilities maintenance and control (Figure 4).

4.4.2 *User Information*

Organization represents institutions, departments or groups occupying a specified space and who have been allocated space. Organisation may exist in one or many locations. Within organisations there may exist groups and individual space occupants. Groups or individuals may also occupy one or several zone locations. For example some groups may use office space as well as laboratory space. Also, individuals may occupy different spaces at different times.

The organization hierarchy (Figure 5) represents the information required about individual occupants in a building. This information is used to evaluate their location as well as their comfort. Individuals will often log complaints or comments about their comfort state in addition to reporting faults.

5 CONCLUSIONS

The sole purpose of any constructed asset, or built facility is to fulfil a need either of business or personal nature. It therefore must meet its clients' needs and interests at commissioning and throughout its life time. A successful facility is not only an answer to the client's basic requirements but it enhances and facilitates the activities which it accommodates.

If building perfomance is monitored and compared with building intent then it will be established that building usage differs from original intent. However if prformance benchmarks have been defined then appropriate modifications may be carried in operation and control to achieve optimum performance. Operation Strategies will be updated as they evolve over the building life cycle by continuously monitoring of building performance and the proper selection of building specific benchmarks. This ongoing comparison between prescribed and real measured data obtained from the building will lead to a tighter coupling between intended operation and building use. The comparison requires definition of conventions which are based on experience of building owner and operators and may be extracted from Operation and Maintenance (O&M) manuals and statistical analysis from past performances.

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A new perspective in supervising building performance

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ABSTRACT: This paper introduces a perspective to supervise buildings performance and operational processes. The aim focuses on the simplification of procedures used in determining a building's performance indicators by harnessing the buildings' physical specifications and sensed data to reduce the building's operational cost and improve its overall performance. This bypasses the limitations of current methodologies and control systems which display questionable scalability and applicability. At the methodological level, the perspective adopts the integration of Data Mining and buildings performance indicators' assessment standards. The authenticity of this approach is validated by mining models currently used by the ITOBO project. This paper further discusses options to extend this approach to support different type of buildings.

1 INTRODUCTION

Building performance supervision engages complex sensing equipment and sophisticated building design features. This includes well operated Hybrid-HVAC (Heating, Ventilating and Air Conditioning) systems with complicated cooling/heating concepts and operational and maintenance processes (Pfafferott, et al. 2007, Keane 2005).

Building performance assessment requires the determination of its indicators. This involves the measurement of energy, lighting, thermal comfort, operational processes and maintenance according to the interests of buildings' owners, operators, and occupants (Augenbroe and Park 2005, O'Sullivan, et al. 2004).

Increasing cost of building supervision and the inadequacy and limitation of current standards and methodologies to determine building performance indicators has attracted solutions (Yao, Li and Liu 2009, Moujalled, Cantin and Guarracin 2008). These include the utilization of Information and Communication Technology (ICT), such as Data Mining (DM) (Kasabov 1998, Sharples, Callaghan and Clarke 1999, Cash, et al. 2003).

This research chooses the exploitation of data mining. The aim focuses on the simplification of procedures used in determining a building's performance indicators, by the utilization of buildings' physical specifications and reduction of equipment.

1.1 *Data Mining concepts*

DM techniques involve extracting knowledge from large amounts of data to support decision making (Wang and Huang 2006, Han and Kamber 2006, Oracle 2008).

DM models, in general, consist of a set of cases or mathematical relationships. These relationships are created, using algorithms, based on an existing knowledge through observing the influences (characteristics) that indicate a specific behavior in a huge amount of data, where a solution to a problem is already known. This process is known as building a model, through which the model is trained to "learn" from the observations. The goal of DM is to utilize this past knowledge to automatically predict a solution to new similar problems, with certain confidence (probability), as the influences indicating the behavior are encapsulated in the model with sufficient generality. This process is known as scoring or applying a model. In the case of Oracle Data Miner (ODM) (Oracle 2008), the mathematical and statistical relationships along with the best algorithm that defines these relationships and test metrics of models' efficiency are taken care of by the ODM engine. Predictive confidence is the effectiveness of a model on whether it "learned" sufficiently from the training process and its ability to generalize this knowledge in different data sets compared to a naïve guess.

1.2 *The ERI building*

This research uses the Environmental Research Institute (ERI) (Keane 2005, O'Sullivan, et al. 2004, ERI 2010) building as a full-scale test bed to prove the authenticity of the results obtained by adopting this perspective.

The ERI supports a Building Management System (BMS) consisting of wireless and wired

Table 1. Data volumes.

Sensors	Sampling period	Total records
180 Wired	15 minutes	6,307,200
80 Wireless	1 minute	42,048,000
Total volume		48,355,200

sensors along with meters and actuators, with 13 different types of measurements, including indoor environment and outdoor weather conditions. Accordingly, this research uses real sensed data from the building. The active sensors data stream volumes for the ERI per year, from all the devices installed is shown in Table 1.

The methodology of this perspective is detailed in section 2. Section 3 explains assessing building performance while section 4 discusses controlling operational processes adopting the perspective. Discussions detailing the advantages of the approach and enhancements conclude this paper.

2 METHODOLOGY

This perspective adopts training DM models to predict building performance indicator values.

In the case of the ERI building, indicator values were calculated based on current international standards.

These values are then used along with the building's physical specifications and the minimum number of equipment to train a mining model to predict them.

The following outlines the implementation of this methodology for the determination of occupants' thermal comfort and natural indoor illuminance levels in the ERI rooms.

2.1 *Occupants' thermal comfort*

Predicted Mean Vote (PMV) was used as the standard to determine occupants' thermal comfort.

The PMV depends on the air temperature, radiant temperature, relative humidity and air velocity, as well as occupant's clothing and activity levels. These measurements are available for 4 rooms in the ERI database. To compute the PMV, a constant air velocity of 0.1 m/s was assumed, which is a representative mean value for naturally ventilated offices as in the case of the ERI. An activity level office works with 1.2 met was assumed. The clothing value was interpolated depending on the outside temperature between 1.0 m^2 K/W (indoor winter clothing at 0°C) and 0.5 m^2 K/W (summer clothing at 30°C PMV depends on air temperature).

The PMV was calculated for the four rooms based on the classification on This model was then used to determine occupants' thermal comfort values for the 70 rooms in the ERI. This is possible because the weather conditions and rooms temperature indicate the thermal comfort is encapsulated in the model with sufficient generality.

The implementation of data mining models of ODM requires preparing a table of relevant inputs. This shows the simplification over using the PMV by itself, in determining the relevant performance indicator by adopting this approach. The input table includes room temperature and outside weather condition measurements. Additionally, the number of sensors per room was reduced by three. The outside weather conditions can be obtained from any weather station relevant to the building location.

This model had 85.28% predictive confidence. This is because the model was based on the PMV values, which was calculated using real sensed data sampled in 15 minute intervals. The model development is further detail in (Ahmed, Ploennigs, et al. 2009).

Table 2 for three years. A dataset consists of these classes along with the rooms' temperature measurements, for the four rooms, and outside weather conditions were used to train a classification model to predict the thermal state for the rooms.

This model was then used to determine occupants' thermal comfort values for the 70 rooms in the ERI. This is possible because the weather conditions and rooms temperature indicate the thermal comfort is encapsulated in the model with sufficient generality.

The implementation of data mining models of ODM requires preparing a table of relevant inputs. This shows the simplification over using the PMV by itself, in determining the relevant performance indicator by adopting this approach. The input table includes room temperature and outside weather condition measurements. Additionally, the number of sensors per room was reduced by three. The outside weather conditions can be obtained from any weather station relevant to the building location.

Table 2. Thermal classes' definition.

Comfort class	Classification
Hot	$3.5 > PMV \geq 2.5$
Warm	$2.5 > PMV \geq 1.5$
Slightly warm	$1.5 > PMV \geq 0.5$
Neutral	$0.5 > PMV \geq -0.5$
Slightly cool	$-0.5 > PMV \geq -1.5$
Cool	$-1.5 > PMV \geq -2.5$
Cold	$-2.5 > PMV \geq -3.5$
Out of range	Otherwise

This model had 85.28% predictive confidence. This is because the model was based on the PMV values, which was calculated using real sensed data sampled in 15 minute intervals. The model development is further detail in (Ahmed, Ploennigs, et al. 2009).

2.2 *Natural indoor illuminance distribution*

Day Light Factor (DF) was used to determine natural indoor illuminance levels.

The simplest way to define DF is as the ratio of interior illuminance '*Ein*', at a given point, to available external illuminance '*Ext*' expressed in per cent, as shown below.

$$DF = Ein/Ext \qquad (1)$$

The sky component '*Sc*', externally reflected component '*Erc*' and internally reflected component '*Irc*' describe the DF and influence its level. The relationship between these components is expressed in equation 2 below.

$$DF = Sc + Erc + Irc \qquad (2)$$

DF can be determined in many ways. This research chooses 'Ecotect' from Autodesk. The approach was to employ Ecotect to determine the lowest DF for each room in the building during a working year. The outside light measurements obtained from the ERI BMS.

Using the historical outside light level measurements in the data base, which were recorded every 15 minutes on a daily basis for the last three years, the natural indoor illuminance levels for each room were calculated using the DF as obtained from equation 1.

A data set comprising of the ERI physical specifications and outside conditions was prepared. Conditions include outside light, diffuse and total radiation, and local weather outlook.

A regression model was trained on this data set to observe correlations between outside conditions and natural indoor illuminance levels. This enables the prediction of these values possible for other buildings providing the relevant inputs.

This shows the components that describe DF and influence its level i.e. sky component, externally reflected component and internally reflected component. These components are integrated into the model as the model based on the DF. This also includes the surface area of the windows excluding frames, bars, and other forms of obstruction, the angle of visible sky from the mid-point of the window, the maintenance factor of the window, the transmission factor of the glazing, the total internal surface of the room and the average reflection factor of all internal surfaces. In fact, some of these factors are included in the model's input, which adds power to the regression model.

Furthermore, the calculations of natural indoor illuminance are calculated using building physics. This eliminates the need for simulation programs to determine the lowest DF for each room. This model had 94.99% predictive confidence. The model development is further detail in (Ahmed, Michel, et al. 2010).

3 BUILDING PERFORMANCE ASSESSMENT

The adequacy of buildings design with respect to natural daylight utilization and thermal comfort state is explained in this section.

3.1 *Natural daylight utilization*

Offices and labs in the ERI were designed to have a minimum of 500 LUX and 150 LUX respectively.

Thus, to assess the adequacy of the ERI design with respect to natural day light utilization, the measurement of natural indoor illuminance is required for the period of evaluation.

These measurements are available by the use of the regression model in section 2.2. There is no need to carry out the calculations of DF and natural indoor illuminance.

According to the ERI daylight specifications the natural indoor illuminance values were transformed into 'adequate' for the values greater than 500 LUX and 150 LUX for offices and labs respectively. All other values are labeled 'not adequate'.

A dataset, consisting of these values, building physical specifications and outside conditions (as for the regression model) over a 3 years period was built.

A classification model was then trained to predict these classes, i.e. 'adequate' and 'not adequate' based on the input mentioned above.

This facilitates the evaluation of proposal designs and existing buildings, changes in offices layouts or façade renovations in order to improve energy efficient and performance in buildings. This model had 99.93 predictive confidences. The model development is further detail in (Ahmed, Michel, et al. 2010).

3.2 *Occupants' thermal comfort*

The classification model in section 2.1 allows the evaluation of existing buildings designs adequacy. As the model outputs the thermal classes based on the PMV classifications.

4 OPERATIONAL PROCESSES CONTROL

This section arranges the developed models (illuminance and thermal) to create an improved Decision Support System (DSS) (Rob, Coronely and Crockett 2008) to assist in optimizing the interrelationships between energy management and occupants' comfort.

4.1 *Scheduling rooms for usage*

This subsection describes a model to achieve savings in artificial light by the utilization of natural light in a comfortable environment.

This was facilitated by the employment of the illuminance and occupants' thermal models. The thermal classes and illuminance levels output, from the corresponding models, were used to define the choice classes (scheduling) shown in Table 3.

A dataset of the scheduling classes, building physical specifications and outside measurement for three years was built. A classification model was then trained to predict choice classes. This model had 86.76% predictive confidence.

The advantage of this model is that it uses weather conditions. If forecast weather data is provided to the model, the model can make a prediction for low-energy comfortable rooms. This is probable because weather conditions and buildings physical specifications that indicate low-energy comfortable rooms are encapsulated into the model with sufficient generality.

This showed supervising building future performance at almost no cost. The model development is further detail in (Ahmed, Korres, et al. 2010).

Table 3. Definition of the scheduling classes.

Thermal	Illuminance	Choice	Meaning
Neutral, Slightly cool, Slightly warm, Cool	Enough	One	Neither artificial light nor heating or cooling is needed
Neutral, Slightly cool, Slightly warm, Cool	Not Enough	Two	Artificial light is needed, no heating or cooling is needed
Cold, Warm	Enough, Not enough	Three	Both artificial light and heating or cooling is needed

4.2 *Managing HVAC systems*

In this section rooms' energy consumption was estimated facilitating the adjustment of energy consumed based on relevant rooms' temperature set points.

The rooms in the ERI are heated via under-floor heating systems. Based on a room's setting point for air temperature, a valve opens and closes.

The heating system is fed via solar panels and geothermal heating pumps. A boiler is triggered when the panels and pumps are not able to provide the required hot water flow rate.

The ERI hybrid HVAC system has also an increased complexity that renders it harder to analyse the building's performance down to the room level. To identify rooms with unusual high heat usage the room's heat consumption needs to be analysed.

Instead of installing heat meters in each room to measure the individual heat consumption, the room's heat intake is estimated from the overall heat consumption of the under-floor heating system. The main problem in the ERI is that information about the control values at the valves is not available in the BMS system.

The basic assumption for the estimation is that only these rooms consume heat which valves are open and allow the hot water to circulate through the under-floor heating circuits.

In summary, a buildings room's heating consumption can be estimated in each time step $k \in \mathbb{N}_0^+$ by the following algorithm:

1. Compute the room's control values and valve opening for each room.
2. Compute the building's actual heating coefficient (which the algorithm provides equations for it).
3. Estimate the room's heat flow. (Based on the equations provided).

This shows that adopting a complex hybrid HVAC system, ICT can provide solutions with no need to install additional controllers. The algorithm development is further detail in (Ploennigs, et al. 2010).

5 DISCUSSION

The building performance assessments domain exhibits constraints as the unavailability of equipment involved in measuring, assessing and managing building performance. This restricts their scalability and applicability. Furthermore, inadequacy of criteria used to determine these indicators and the approaches used, which involves simulation and laboratories, do not precisely reflect real time situations.

The involvement of complex hybrid HVAC systems that require sophisticated building features and operations and maintenance processes, minimizes the saving intended by building supervision.

The perspective introduced in this paper makes use of building physical specifications and features. It decreases the cost of monitoring equipment and effort in performing calculations. It also, reduces data volumes and management.

The acceptance of integrating international standards improves models quality. In parallel, this is also an opportunity to improve these standards. It assists by supporting additional buildings' elements that may affect the corresponding performance indicators.

The presented perspective gives an overview of building physical specifications and its impact on performance indicators. This, with the ease of implementation, i.e. a simple table of inputs, facilitates adequate design with respect to energy-efficiency. It also allows improving existing buildings performance.

At the applicability level, the perspective scales up to different building types. The ability of using the available information about building geometry extends model applicability.

The possibilities to improve the models developed are high. This can be attained by training the model from data from different weather stations in multiple proposals designs.

6 CONCLUSION

A new perspective to supervise building performance was introduced. It adopts the integration of data mining, buildings' physical specifications and performance indicators standards. The motivation of this integration is to simplify the procedures used to assess building performance.

The results show, occupants' thermal comfort can be determined using one temperature sensor per room and outside weather conditions. Natural indoor illuminance distributions can be calculated using one outside light sensor and building physical specifications.

Building operational processes can be controlled by the use of building physical specifications and weather forecast data.

The overall building performance, for the exiting building and proposal designs, can be assessed by the use of building geometry and data from weather stations relevant to the building locations.

A research to improve the developed mining models is ongoing. Implementing this perspective to the building maintenance domain is underway.

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A Framework Architecture for Optimised Building Operation

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ABSTRACT: This paper describes a Framework Architecture for Optimised Building Operation developed as part of the Strategic Research Cluster ITOBO (Information Technology for Optimised Building Operation). The cluster is funded by Science Foundation Ireland and supported by five industry partners. The Framework Architecture presented in this paper informed and guided the R&D activities of the SRC from 2008 to 2010. It resulted from an intensive requirements elicitation process jointly performed by research students and ITOBO's industry partners. The Framework Architecture is documented in UML (Unified Modelling Language). It is divided horizontally in three layers; the Data Acquisition Layer, the Data Management Layer, and the Data Processing & Representation Layer. An additional vertical structure allows us to distinguish into domain specific support tools, such as the Control Pillar (Electrical Engineering), the Maintenance Management Pillar (Facility Management), the Energy Management Pillar (Mechanical Engineering) and a Model Development Pillar (Civil and Mechanical Engineering). The core Framework Structure is complemented by Use Case Definitions and Information Processing Sequences.

1 INTRODUCTION

1.1 *The challenge*

The Strategic Research Cluster ITOBO aims to develop a Hardware-Software Platform which supports the optimised operation of buildings over their whole life cycle. Even if not all aspects of building management are addressed—since the ITOBO-focus is on energy in buildings—it is obvious that many components are needed to deliver the required functionality. The spectrum of tools ranges from design support and model building through energy simulation, performance monitoring, building control and performance diagnosis down to maintenance management including scheduling and collaboration support.

In terms of information and data management different functionalities need to be provided, such as data acquisition, data exchange and data integration, information generation through categorization, data aggregation, compression, analysis, and mining; and information processing by putting data and information in a domain specific context.

The following paper will describe the development process of the Framework Architecture, the Individual Components and the available mechanisms for data and information exchange and processing within the specified Framework Architecture.

1.2 *The development process*

The work described in the following paper documents results of the early phases of the software development process. Work started with a Requirements Elicitation Phase. The result of this phase led to a better understanding of stakeholders involved in Building Life Cycle Management, their major activities and a rough understanding about the required ICT support of these activities.

During the requirements analysis phase we considered available ICT-components, evaluated their functionality, identified shortcomings and development needs. We also identified functional and non-functional requirements, the major functionalities and the quality in which they must be provided. Last but not least we identified major blocks of data that need to be exchanged, the sequence of required steps to process this data, the tools required to manage, store, and back-up this data.

Finally, during Systems Design we identified major Information Objects required, we went through an initial hardware-software mapping phase and identified off-the-shelve components which could and should be used to support our research activities and to allow us to concentrate on improvements and research challenges.

2 REQUIREMENTS ELICITATION

2.1 *Stakeholder identification*

Numerous stakeholders are involved in Building Life Cycle (BLC) activities, such as architects and engineers in the Design Phase, engineers and component manufacturers in the Construction and Commissioning Phase, or managers and operators in the Operational Phases of the BLC.

A key stakeholder is the building user—a tenant of an apartment, the user of an office, or the worker in a factory. He/she requests a certain comfort level (QoS). The provision of the QoS requires the consumption of a certain amount of energy. However, the QoS is also influenced by user preferences which determine the intensity of demanding certain parameters of User Comfort.

Last but not least the Owner of the building is involved in all phases of the BLC and has a constant need for information being usually delivered in a compressed and aggregated way.

Table 1 below gives an overview about the major stakeholders involved in Building Operation (including the design phase which heavily influences the Operational Phase). The work in ITOBO addresses primarily stakeholders being active in the building operation phase.

As part of the EU-FP7 project intube (Menzel 2009a) an intensive stakeholder analysis was performed and is documented in multiple publications and reports.

2.2 *Information needs*

The major information requirements for the identified stakeholder profiles are specified in Table 2.

The intube stakeholder analysis was complemented by an information flow analysis describing

Table 1. Stakeholders and level of engagement.

	Systems' specification	Systems' design	Systems' commissioning	Systems' operation
Building owner	○	○	○	⊙
Architect	●	●	⊙	
Engineer	●	●	●	⊙
Building operator	⊙		●	●
Facility manager		⊙	⊙	●
Energy manager	⊙	⊙	⊙	●
Building user			⊙	○

LEGEND: ○..decides, ⊙..advices, ●..acts

Table 2. Information requirements.

	Building owner	Architect, engineer, Building operator	Facility manager, Energy manager	Building user
Component specification		●	●	
Process specification		●	●	
Financial information	●	●	●	
Component status	●		●	●
Control commands			●	

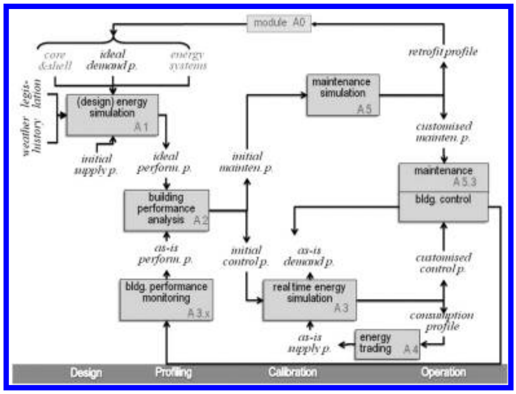

Figure 1. Major BLC activities and information flow.

the major engineering activities related to energy simulation for building design and energy management in buildings. Energy related information needs were described in so called intube-Energy-profiles. The information flow is specified in IDEF-0 notation and shown in Figure 1.

Table 3 below maps the information requirements presented in Table 2 to Energy Profiles (Figure 1).

A more detailed specification is developed and documented in (Menzel 2009b).

3 REQUIREMENTS ANALYSIS

3.1 *Available ICT components for data acquisition and actuation*

Within ITOBO we distinguish into three different elements for data acquisition and actuation; namely wired sensor/actuator infrastructure, wireless sensor/actuator infrastructure and RFID components. The sensor and actuator components have multiple similarities in terms of their higher level

Table 3. Content of energy profiles.

	Supply profile	Demand profile	Performance profile	Operation profile	Consumption profile	Maintenance profile	Retrofit profile
Component Spec.: External shell			●				
Product Spec.: Geographic location			●	●			●
Product Spec.: Mechanical Systems	●		●		●	●	
Process Spec.: Weather data				●			
Process Spec.: Comfort Specification		●		●		●	
Process Spec: Demand/Supply	●	●	●	●	●		
Financial information: tariffs	●				●		
Financial information: Maintenance costs						●	●
Control commands				●			

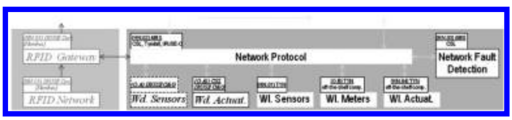

Figure 2. Package diagram network & Data Acquisition Layer.

data and information management components. They are distinct from each other through their different Networked Embedded Software Components (see also McGibney 2008).

Figure 2 below depicts the major ITOBO components of the Data Acquisition and Actuation Layer using the notation of UML Package Diagrams.

ITOBO contributes to the development of two IEEE 802.15.4 compliant network protocols. The Networked Embedded Systems software installed on the ITOBO-motes extends the ZigBee protocol. However, ITOBO operates a hybrid network hierarchy using Sokres Network PC as FFD. These devices also run the 6lowpan protocol stack which allows us to propagate sensor readings using TCP/IP from the Network PC to the Data Warehouse Server using the ITOBO middleware layer.

3.2 *Available ICT components for data management*

ITOBO needs to manage four different types of information; such as Product Specifications, Process Specifications, Performance Specification and Performance History Information.

Numerous publications are available about Product Modelling in Architecture, Engineering, and Construction [Eastman 2008]. There are two major, well developed standards which support the standardized information modelling and the information exchange of product model information specifying the core and shell of buildings; the Industry Foundation Classes and the Standard for the Exchange of Product Model Data (ISO 10303). Multiple vendors offer so called product model servers.

Similar to Product Modelling one can find numerous standards, publications and products which support the development of formalized Business Process Models (see also Menzel et al. 2009c). The ARIS-methodology is one of the early developments.

Database Management Systems (DBMS) are available to support the management of bulk data. However, DBMS are not well suited for the management and analysis of historical trends and facts. They lack sufficient support for complex queries and retrieval patterns. Data Warehouse Systems address this deficit by allowing redundant data storage and enabling the storage of pre-processed complex queries and retrieval patterns.

Figure 3 below depicts the components of the ITOBO Data Management Layer using the notation of UML Package Diagrams.

3.3 *Available ICT components for User Awareness*

The simplest form of Energy Management is the stimulation of User Awareness by providing simple

Figure 3. Package diagram data management layer.

monitoring clients for building users. These are usually web-clients with limited and simple functionality for interaction.

Further, more sophisticated, examples of Monitoring Clients are Graphical User Interfaces for Energy and Facility Managers. These GUIs must provide detailed functionalities for user interaction.

3.4 *Available ICT components for Design Support*

ITOBO needs design support for three technical systems; the core & shell of buildings, the building services systems and components, and the wired and wireless sensor/actuator infrastructure.

Many tools exist to support the design activities for the core & shell of buildings, known as so called "Computer Aided Design" (CAD) tools. However, older generations of CAD tools model the drafting process leading to the fact that the information models are based on Geometrical Models and not on Object-Oriented Engineering models. Furthermore, it is advantageous if the underlying CAD-model and the implemented design philosophy supports parametric and feature based modelling of technical artifacts. The ITOBO research focus is not on the development of CAD-tools. Therefore, the ITOBO team went through an initial literature review to identify state-of-the-art model editors for the Architecture and MEP-domain and uses off-the-shelve components.

Numerous Energy Simulation tools are available on the market. However, the supported functionality in terms of supported technical systems and operational scenarios varies. This is especially true if it comes to the integration of renewable energy systems, micro-generation capacities and distributed energy storage capacities. The ITOBO consortium is aware of these deficits. However, we have decided to work with "off-the shelve components" since Energy Simulation is not in the research focus of our Strategic Research Cluster.

Since one research pillar in ITOBO is the development of novel wireless sensor components, we have decided to focus our research on the development of a Methodology and a complementing tool to support the Design of indoor wireless sensor/actuator networks.

The Design Support Pillar of the Application Layer is shown in Figure 5 below using the notation of UML Package Diagrams.

Figure 4. Package diagram monitoring clients.

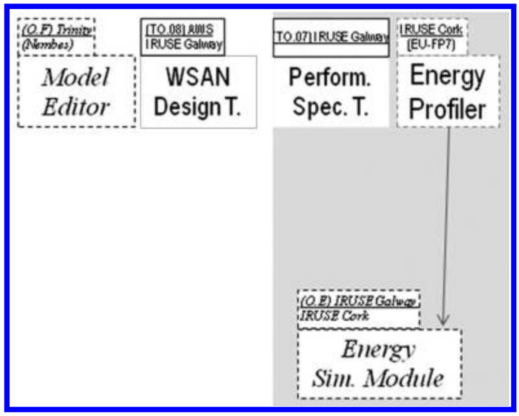

Figure 5. Package diagram design support layer.

3.5 *Available ICT components for Maintenance Management*

Maintenance Management is supported by multiple software packages; (i) the Maintenance Clients, (ii) the Maintenance Management System, (iii) the Diagnosis Module, (iv) the Scheduling Package, (iv) the BMS-Fault Detection Package, and (v) the Model Editor.

Figure 6 below depicts the components of the Maintenance Management Pillar of the ITOBO Framework Architecture using the notation of UML Package Diagrams.

The Model Editor is an "off-the-shelve component" which is used to develop the ITOBO competency models in the standardized and formalized Business Process Modelling Language ARIS. Process specifications are provided in the form of so called extended Event Process Chains (sEPK). A more detailed description about eEPK can be found in (Menzel 2006).

The Maintenance Clients provide an interface to the Maintenance Management System and the Scheduling Component.

The Maintenance Management System (MMS) is introduced to support collaborative work scenarios. It's primary functionality is to configure the "Competency Blocks" (modeled as extended

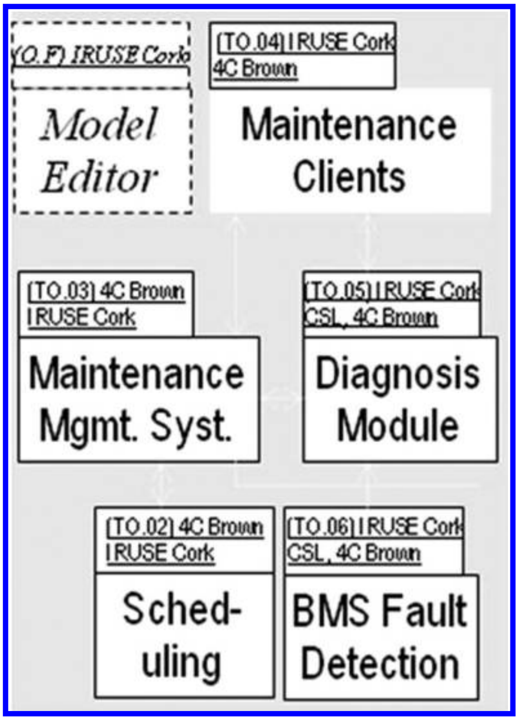

Figure 6. Package diagram maintenance management layer.

Event-Process-Chains in ARIS). The MMS then closely interacts with the Maintenance Scheduler package which optimizes the sequence of maintenance activities using the resource availability, the room availability and additional cost occurring from delayed maintenance.

The BMS-Fault Detection Package deploys Data Mining techniques in order to identify slow degradation of building services systems and components. (see Ahmed et al. 2009).

Finally, the Diagnosis Module allows the Facility and Energy Manager to diagnose a complex systems to identify malfunctioning devices. It is the goal to dramatically reduce the number of error messages of BMS (see Provan et al. 2009).

3.6 *Available components for Building Control*

The Building Control Pillar consists of four Packages, the User Interface, the Preference Analysis Package, the Prediction Analysis Package and the Intelligent Control Module. Components of this pillar will provide advanced control functionality to improve the precision, flexibility, and adaptability of control scenarios and the underpinning algorithms (Madi et al. 2009) and (Madi et al. 2010).

Within ITOBO phase 1 we considered a two step approach with a higher level controller periodically optimizing initial settings, combined with a lower level controller actuating the lights. ITOBO formulates the higher level problem as constraint based optimisation. The higher level controller provides new set-points for the reactive controller which then maintains the desired user comfort levels by actuating the relevant devices. Initial work is focused on lighting control. Figure 7 below shows the major components of the Intelligent Control Pillar of the ITOBO Framework Architecture using the notation of UML Package Diagrams.

One major function of the Control Interface is to collect feedback from users about the satisfaction levels. Alternatively, the Preference Analysis Package offers a functionality to learn over time based on user actions with regard to dedicated building services components (see also Schumann et al. 2010).

It is planned that the Prediction Analysis Package applies user preferences but also weather data to the physical environment. We plan to break down user preferences into control zones, each of

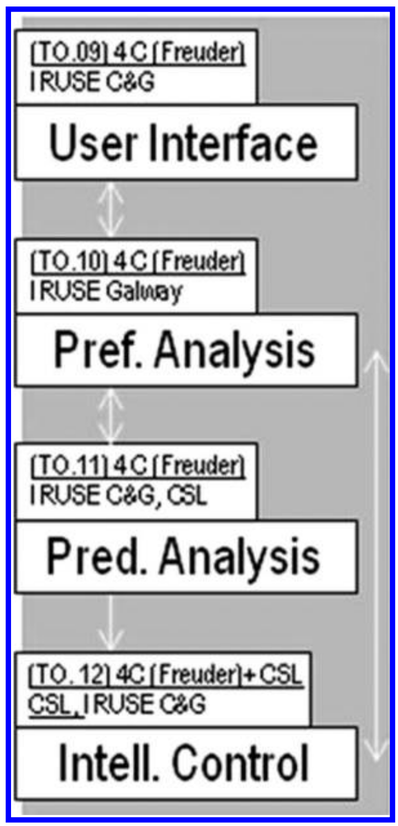

Figure 7. Package diagram control layer.

which contains a set of zero or more occupants. By averaging the preference curves of the relevant set of occupants, we produce a zone preference curve, which describes the overall satisfaction of that set of occupants.

The intelligent controller is responsible for computing on request settings for the actuators which optimize both energy consumption and user satisfaction. To this end ITOBO models the energy cost and the effect on the building environment of the actuators, and the preferences of the occupants as a Constraint Problem.

4 SYSTEMS DESIGN

4.1 *The overall system*

The paragraph aims to synthesize the previously described layers and packages forming the overall ITOBO Framework Architecture. As shown in Figure 8 below, the three horizontal layers—Network Layer, Data Layer, and Tool Layer—are further detailed into individual packages.

The break down in software packages allows us to divide the workload in clearly identifiable research tasks and prototypical implementations for the Proof-of-Concept which could be clearly assigned to individual PhD-students and Post Doctoral Researchers.

Furthermore, the combination of multiple modular packages allows us to compile more complex demonstration scenarios from initial research achievements.

Finally, the required hardware software mapping is easily supported by this structure.

4.2 *Hardware software mapping*

The hardware-software mapping is specified using the UML deployment diagram technique. The principal ITOBO Hardware Architecture Framework

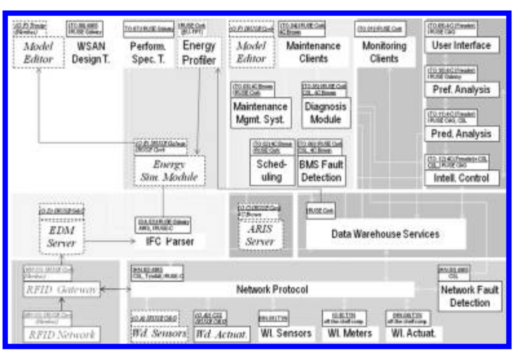

Figure 8. Detailed ITOBO Framework Architecture.

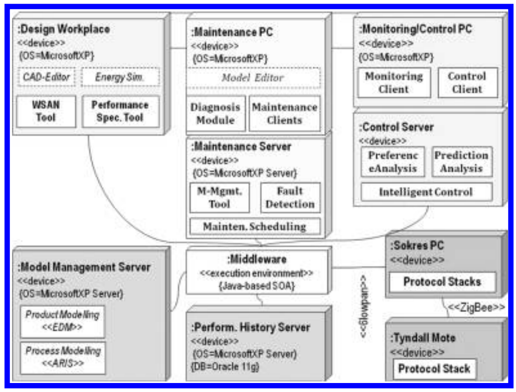

Figure 9. Deployment diagram / Hardware-software mapping.

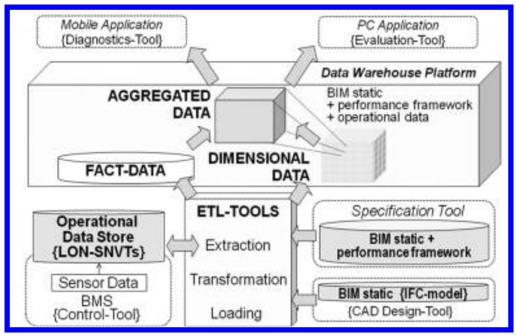

Figure 10. Major information objects.

is specified in Figure 9 on the next page. One can see, that the complete ITOBO system consists of three clients—the Design Workplace, the Maintenance PC, and the Monitoring & Control PC—and four different servers—the Model Management Server, the Performance History Server, the Maintenance Server, and the Building Control Server. Additionally, the ITOBO platform is complemented by a Network PC component and the multifunctional Tyndall motes.

4.3 *Major information objects*

The ITOBO platform manages data and information from different sources. This paragraph focuses on the information management of Performance History Data and Building Information Model Data. The information flow and the major information objects are described in Figure 10 below.

The left hand side of Figure 10 describes the information flow of the sensed and metered performance data but also data documenting the status of actuation devices. This data is considered to become Fact Data in the ITOBO-Data Warehouse Platform. Fact Data describes the status of a system, component or zone at a dedicated time. The fact is recorded and the value will never change.

On the right hand side of Figure 10 the information flow of so called Dimensional Data is specified.

This data is imported from Building Information Modelling tools (BIM), such as CAD, and imported into the ITOBO Data Warehouse. This data is used to classify and categorize the Fact Data. Possible categorization is according to time, location, or organization.

Through the application of aggregation and evaluation rules/procedures Fact Data can be aggregated or analyzed. The results of these data processing steps are stored in so called "Data Cubes" in the Data Warehouse Platform. Data Cubes are implemented as so called Materialized Views in Oracle.

A more detailed description of ITOBO information objects can be found in Deliverable D5-2.

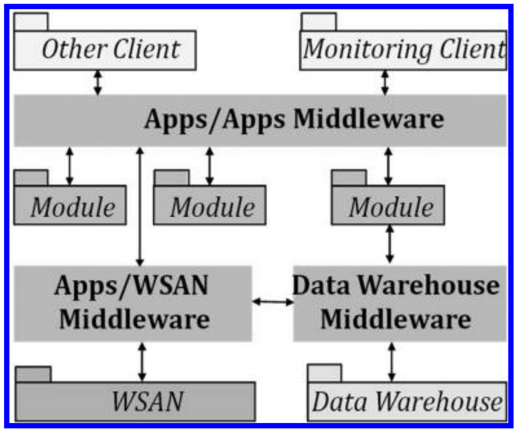

Figure 11. ITOBO middleware architecture.

5 MIDDLEWARE

The middleware platform for ITOBO includes four middleware layers. The Apps/Apps Middleware acts as the broker of all services, and also the portal for ITOBO. Data Warehouse Middleware devotes itself to access the Data Warehouse. WSAN middleware is divided in two layers. The top layer, Apps/WSAN Middleware, works on an embedded PC and connects between applications and WSAN middleware. WSAN Middleware is the lower layer and sits between WSAN and Apps/WSAN Middleware.

5.1 *Apps/Apps middleware*

The middleware module acts as the broker for all middleware services. Because SOA requires a public registry for service providers to register their services and consumers to find these services, the Apps/Apps middleware can work as service registry (broker). These services come from all modules and other middleware. This means every module is a provider of a service or requestor of a service.

The Apps/Apps middleware can also act as a portal for ITOBO, since it integrates all client modules and provides uniform entry for all clients. Every client does not install client modules on their PCs or laptops. They only need to login to the Apps/Apps middleware. Relevant GUIs will display while different clients login. For example, the GUI of monitoring module will only display when a monitoring client login. If the client supports maintenance and monitoring permissions, the GUI composing maintenance and monitoring modules will display (see also Stack 2009).

5.2 *Data Warehouse Middleware*

The Data Warehouse can be accessed through a shared interface (DB_WSN) which specifies the functions offered by the Web service. Both the client and server side implement this interface. This allows both services to be directly connected without the web service if needed. If they run on the same machine and for performance reasons should be connected directly.

A DB_WSN_Server implements the service process and connects to the Oracle Data Warehouse via a Java Database Connectivity (JDBC) interface. The server is published by the JAX-WS framework on the web and a WDSL describing the server interface is automatically created. The client service code can be generated from this WDSL.

Once a message is received on the client side (e.g. to compile temporarily stored readings from sensor devices), the client extracts the message data and sends it to the DW service via the client interface. The handling of the XML messages is completely encapsulated by the JAX-WS and doesn't need to be implemented. A Boolean value is returned from the server to inform the client if the data submission was successful.

5.3 *Apps/WSAN Middleware*

The Apps/WSAN Middleware is a bridge to connect the WSAN with application services, such as Data Warehouse services, IFC Parser services and diagnosis module services. It consists of two layers a software layer deployed on top of the WSAN middleware layer (Aslam et al. 2010).

The communication with the WSAN Middleware is implemented using the UDP protocol since the current WSAN uses blip(b6lowpan). Web-services are used for communication, a web-service client is designed to forward the received WSAN messages to the Data Warehouse services, and another web-service server is used to communicate control decisions to the WSAN.

The main purpose of the WSAN middleware layer is to address challenges in relation to development, maintenance, deployment and execution of applications over a WSN. The main features are: (1) Heterogeneity (multi vendor support), (2) Efficient data transmission (low energy consumption), (3) Error detection and recovery (re-routing), (4) Reprogramming over-air.

6 IMPLEMENTED SCENARIOS

Based on the discussions with the project's industry partners in Spring and Summer 2008 and the results of a workshop held in Frankfurt/Main (Germany) in Autumn 2008 the following four scenarios were identified as most relevant for the future work in the ITOBO project:

- Scenario 1: Data Representation & Aggregation
- Scenario 2a: Sensor/Actuator Network Design
- Scenario 2: Building Perform. Analysis & Diagnostics
- Scenario 3: Scheduling and Management of Maintenance Activities
- Scenario 4a: Preference Modelling
- Scenario 4: Intelligent Building Control

Scenario 1 addresses the need for easy understandable representation of different data streams to various stakeholders. Compiled performance data includes: Energy Consumption Data (conventional and renewable sources), User Comfort Data (Temperature, CO_2-level, Humidity, Lux-Level), Environmental Impact Data (CO_2-Footprint).

Scenario 2 addresses the need to carry out automated building performance analysis and diagnostics based on the systematically developed building performance specification tool. This scenario entails developing a Fault Detection System that can signal anomalous system behaviours, and a Model Based Diagnosis Module that isolates the root fault entailed by any anomaly signalled by the user or automatically detected by the Fault Detection System.

Scenario 2a addresses the need to optimally design and layout a wireless sensor and actuator network.

Scenario 3 addresses the need for effective planned and reactive maintenance of the building. Maintenance actions will be derived from (a) regular maintenance requirements and processes, (b) user reports and (c) building performance data and diagnosis. The actions will be scheduled to optimise energy efficiency, cost and user satisfaction, while respecting constraints and preferences over resources, engineer availability, and building use. The schedule will be updated continuously as tasks are completed, as engineers report their locations, and as new tasks are generated. Particular attention will be paid to the roles of multiple service teams, requiring negotiation of contracts and service levels, and coordination of activities between the teams. Relevant technical documentation and work orders will be compiled. Information will be forwarded in a context sensitive way to the individual maintenance clients (mobile and desktop).

Scenario 4 will finally use all components of the ITOBO Framework Architecture. It is the most complex scenario. Building occupants and building operators can express their preferences via the User Preference Interfaces; the information is processed by the Preference Analysis module. The Predictive Analysis module takes building usage data from the Data Warehouse, and predicts occupancy. This information about user occupancy is henceforth called "Building Use Model". The Intelligent Control module interacts with the Preference Analysis, Predictive Analysis, and Data Warehouse modules to compute control parameters, which are then passed to the wireless network for actuation. It also can feed information to the diagnosis module regarding control problems, as well as the Maintenance Management System, to request repairs of known faults. Also, information from the maintenance management and diagnosis systems may be used to influence the control policy.

7 SUMMARY AND CONCLUSIONS

This paper presents a Framework Architecture for Optimised Building Operation jointly developed by researchers and industry partners of the Strategic research Cluster ITOBO.

Development commenced in Summer 2008 with a Requirements Elicitation phase. The version presented in this paper was approved by all consortium members in Spring 2009 and has guided and informed Research and Development activities of the SRC since then. The modular approach has enabled ITOBO researchers to bundle intermediate research results into Demonstrators. These Demonstrators were installed in at least one of the ITOBO Living Laboratories [Menzel 2010a].

In many cases "Proof of Concept" could be developed and efficiency gains and/or energy savings could be verified.

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Interactive refinement of distributed Control/WSAN design for optimal building operation systems

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ABSTRACT: Control systems which are embedded in a Wireless Sensor/Actuator Network (WSAN) can perform sub-optimally if the control system and WSAN are designed independently. In Building Management System (BMS) applications, such sub-optimal performance can result in lower user comfort and potential control instability. In this paper, we provide a methodology for a WSAN/Control co-design that identifies design requirements that jointly optimize over the WSAN and control parameters, thereby leading to high user comfort in multi-zone building applications. The developed methodology has been illustrated through a distributed and a typical PI centralized lighting control developed using our hybrid/multi-agent platform.

1 INTRODUCTION

Nowadays, networked wireless devices are widely used in many applications, such as habitat monitoring, object tracking, fire detection and modern building. In particular, buildings equipped with BMS, where often large wireless/wired sensor networks are deployed. Designing distributed sensor network applications for such systems face numerous challenges in scaling, delays associated with data collection and energy consumption, which can lead to unstable systems. This instability might also be due to the performance tradeoffs between the control and wireless networks when designing the controller.

Control systems and communication networks are typically designed using different platforms and principles. Control theory requires accurate, timely and lossless feedback data; however, random delays and packet loss are generally accepted in communication networks, particularly in wireless networks. Therefore, the performance of the control model relies on the network performance, due to the distribution and communication based control. From the control perspective, the more knowledge the controller has about the system, the better the control performance is. Additional knowledge about the system is obtained by increasing the number of sensors or sending sensor measurements more frequently. However, this increases the communication burden on the network and cause network congestion. The congestion results in longer delays and more packet losses, which degrades the control performance.

The degradation of the reduced Quality of Service (QoS) at the network level means less user comfort; for example, a communication delay results in a delay to reach the optimal set point (i.e. light luminance). Second, packet losses may cause false alarms or a failure to capture real alarm data.

The objective of our work is to provide a design methodology for control and WSAN systems that improves the building control in relation to user comfort, safety and reliability. These factors are dependent on optimal control parameters and enhanced WSAN QoS.

Our research extends prior work in the area, e.g., (Liu, X. et al. 2005), by exploring the impact of the control performance on the WSAN and vice versa. (Liu, X. et al. 2005) provides a cross-layer methodology to link the standard design layers of an Open System Interconnection (OSI). This methodology ignores the performance of the WSAN and moreover, it does not consider linking the performance evaluation of the different layers which may lead to better control performance but rapidly degrades the performance of the other layers. We have selected the MAC protocol and the Link technique design; we do not consider the network layer because the underlying example uses a point-to-point linking technique. The impact of changing the correlated parameters on both control performance and the WSAN QoS has been considered, with priority given to the objectives of the application, as represented in control requirements.

We propose a methodology that tunes performance using two phases. The first considers tuning control performance to get the best correlated parameter values; for this we calculate the parameter variation boundaries. The second one deals with the WSAN QoS; for this we explore the search population within the boundaries provided previously, to determine the optimal Control/WSAN configuration.

The remainder of the paper is organized as following: Section 2 explains the design optimisation approach considering the control and WSAN; moreover the section shows how we can apply this approach on a case study. In Section 3, the case study modelling is discussed. The simulation results, produced from the case study modelling, are discussed in Section 4. Finally Section 5 concludes the paper and highlights the future trends.

2 CONTROL/WSAN REFINEMENT APPROACH

As stated earlier, in modern buildings, distributed controllers over large wireless/wired sensor/actuator network face the challenge of achieving good WSAN performances while designing the control application. The case where both control and WSAN models are designed separately may lead to unstable and sub-optimal implementations. In this research work we assume a high correlation between the performance parameters of both control and WSAN models. For example, if the WSAN has received many requests at a certain moment, this will lead to either delay in responding to the next request (in order to serve all the buffered requests) or dropping some requests which will create unexpected behavior in the environment. In this section we explain our approach for an integrated design of both control and WSAN.

Figure 1 shows the flowchart of the approach:

1. First identify the correlated parameters P_i which mutually affect both WSAN QoS and the control performance.
2. Identify the search space for the P_i with acceptable values $P_i(j)$.
3. With the assumption that the control performance has higher priority, evaluate the control performance (Mean Square Error "MSE") according to the identified search space.
4. Evaluate the MSE according to $P_i(j)$, which indicates the value for P_i at instance j.
5. Repeat step 4 until obtaining acceptable control performance, and hence identify the boundaries $[a_i, b_i]$ for each parameter P_i.
6. Evaluate the QoS of the WSAN within the identified boundaries $[a_i, b_i]$.
7. Repeat step 6 until the QoS equals the predefined stopping criteria for the WSAN.

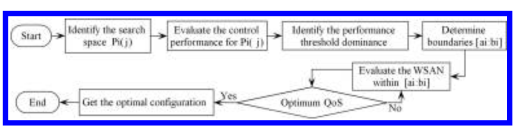

Figure 1. Control/WSAN Co-design flowchart.

2.1 *Lighting example: Parameterizable and Predictable Distributed Controller*

This section introduces our new Parameterizable and Predictable Distributed Controller (PPD-Controller) for automated lighting systems (Mady, A. et al. 2010). The PPD-Controller offers a distributed solution and aims to increase the control reliability, scalability, resource sharing and concurrency.

An open office area with a typical architecture is considered, as shown in Figure 2. It contains 10 controlled zones; each zone contains one artificial light, one light sensor and one Radio-Frequency Identification (RFID) receiver. There are 4 windows/bindings on the right and left boarders of the open area and a fix number of predefined person positions.

The lighting system integrates blinding and lighting controls. It also simultaneously optimizes the light luminance and blind position, depending

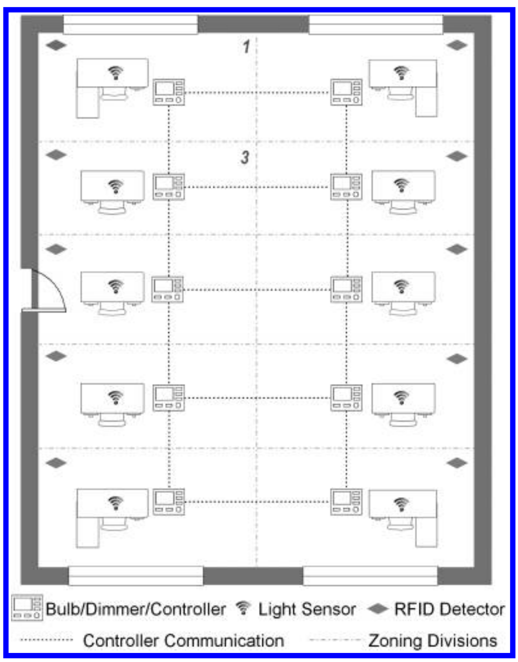

Figure 2. Model specification.

on the user preferences and the power consumed by the artificial light and the blinding actuators.

As a summary, the lighting control scenario behaves as follows:

1. The user can switch on/off the automatic lighting system for several zones, or for all the system through a technician.
2. The users provide their preferences (light luminance and blinding position).
3. A person is tracked in each zone using for example RFID; his preferences are ignored whenever he leaves his zone.
4. A local optimisation engine receives the user preferences and sends back the optimal settings.
5. The local controller controls the artificial light and the blinding actuators in order to reach the user preferences considering the daylight luminance and the light interferences coming from the adjacent zones.

2.2 *Correlated parameter identification*

Through studying the correlated parameter space of the PPD-Controller/WSAN, we have identified that the Sensor Sampling Period (*SSP*), Controller Sampling Period (*CSP*) and Zone Number (*ZN*) are the correlated parameters P_i; in contrast, the centralized controller has only a single correlated parameter, *SSP*.

However, other parameters may affect the WSAN or the control separately; for example, the sampling period for the RFID affects the WSAN QoS but it does not affect the controller. As it is handled by the controller in an event-based model, the controller considers only the occupant presence and not the frequency of the sampling period. We have found, in general, that in the distributed approach the P_i depends on the control strategy, and in the centralized control model the P_i depends more on high *SSP* values.

3 CONTROL AND WSAN MODELLING FOR THE PPD-CONTROLLER

In this section, we briefly describe the control and the WSAN models.

3.1 *Control modelling*

Figure 3 shows the model of a local controller and its interactions with the environments. The preference solver receives the user preferences for each zone, sends the optimal light luminance and blinding position back to the optimisation engine. This latter solver uses Genetic Algorithm/Simulated Annealing (GASA) algorithm (El-Hosseini, M.A. et al. 2008) in order to calculate the optimal

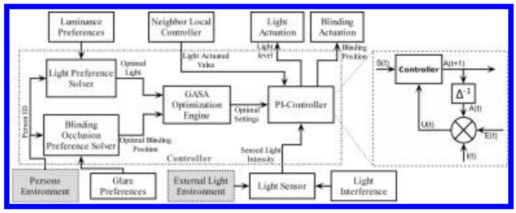

Figure 3. Control model.

actuation settings, and then sends them back to the PI-Controller. The PI-Controller predicts the next actuation setting for the lighting level in a closed-loop fashion (Kolokotsa, D., et al. 2008), using Eq. 1. It actuates the artificial light and the blinding position according to the optimum settings. Whenever preferences change, the optimisation step is updated; otherwise, the PI-Controller actuates based on the external light and the light interference. The Light/Blinding Occlusion Preference Solver agent is used to provide the intermediate solution between several luminance/glare preferences in the same controlled zone. It applies a Low Pass Filter (LPF) in order to prevent exceeding a predefined threshold (700 Lux for luminance and 100% for the blinding position). The control equations are given by:

$$A(t+1) = A(t) + \theta$$
$$U(t) = A(t) + E(t) + I(t)$$
$$\theta = \begin{cases} \gamma - \dfrac{\beta}{\rho} & if\,[U(t) - S(t)] > \varepsilon \\ \dfrac{\beta}{\rho} - \gamma & if\,[S(t) - U(t)] > \varepsilon \\ 0 & if\,|S(t) - U(t)| \le \varepsilon \end{cases} \quad (1)$$

In Equation (1) we use the following notation: A(t) is the actuation setting for light/blinding actuators, E(t) is the daylight intensity (Lux), I(t) is the interference light intensity (Lux), U(t) is the sensed light intensity (Lux), $S(t)$ is the optimal preference settings, ε is the luminance level produced from a single dimming level (70 Lux), β is the maximum light intensity error (700 Lux), γ is the minimal light intensity error (0 Lux) and ρ is the total number of dimming levels (10 levels).

3.2 *WSAN modelling*

In order to evaluate the WSAN performance for the PPD-Controller, we have modeled the WSAN using the VisualSense tool (The Ptolemy Project). We have also considered the Tyndall (Tyndall National Institute) sensor node as a reference for the model parameters. The Time Division Multiple Access (TDMA-based) MAC protocol (Liu, A., et al. 2005) is used in the contention-free period, which leads to a free collision probability. Figure 4 shows the WSAN model used for evaluating 4 zones (1, 3, 4, 5) (Fig. 2). The PPD-Controller in zone 3 has been selected to be evaluated as it constitutes the bottleneck in the model, since it is the most heavily used due to its communication with the other 3 controllers (1, 4, 5), their RFIDs and sensors. In relation to the WSAN performance, the Response Time (Delay) for the network has been considered as the QoS metric (Demirkol, I., et al. 2006).

The Response Time (Delay) reflects the user comfort, whereas we have considered it in the control evaluation metric as well.

When modelling the WSAN for the PPD-Controller, we distinguished four models:

Communication channels model: 2 channels are considered for the wireless communication, one channel for light sensors and the local controllers (Zigbee band, i.e. 2.4 GHz) and other for the RFIDs (RF band, i.e. 324 MHz). The power propagation factor in the communication channels is $1/4\pi r^2$, where r is the distance between the transmitter and the receiver, and the loss probability in each channel is 2%.

Light sensor model: The sensor sends the Lux measured value and the sensor ID to the controller using a fixed sampling rate and frequency offset, as shown in Figure 5. The sensor coverage area is 3 meters (distributed in sphere area) and its power transmission is 0.1 watt/m^2. In order to show the effect of the battery discharging on the sensor transmission range, we have assumed that the range is decreasing by 0.1 meter each event that follows Poisson distribution with mean time equals to 20 times the sensor sampling rate.

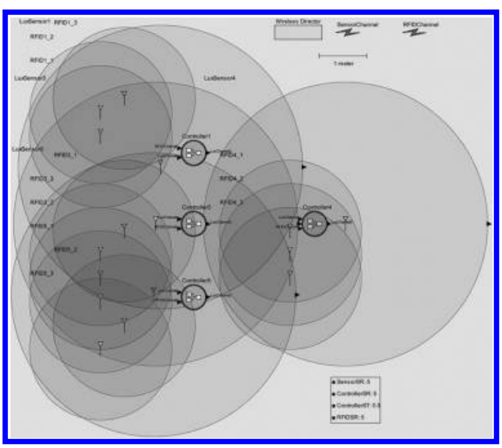

Figure 4. PPD WSAN model.

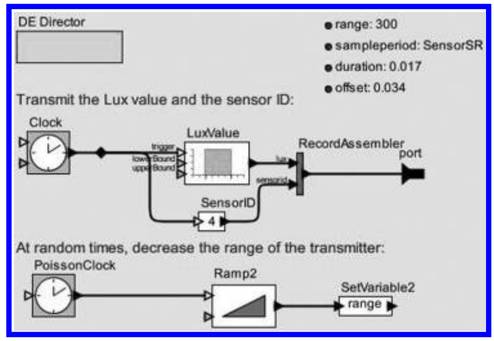

Figure 5. Light sensor model.

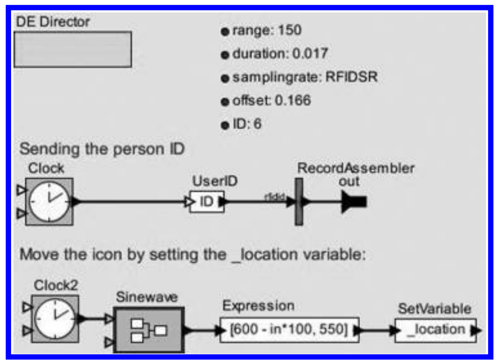

Figure 6. RFID model.

RFID model: The RFID detection range is 1.5 meters and its power transmission is 0.1 watt/m^2. As shown in Figure 6, the RFID sends its ID with a fixed sampling rate and frequency offset. Moreover, the movement of the RFID is modeled as a sin wave sampled every 0.3 minute.

Controller/Receiver model: In this model, shown in Figure 7, we have considered the received packets number, buffer size and the controller duty cycle. However, the controller service time is fixed per received packet. The communication between the neighboring controllers also uses the sensor channel.

4 EXPERIMENTAL RESULTS

In this section we describe the results of applying the proposed methodology to design the PPD-Controller and its underlying WSAN model. It integrates for comparison purposes, the results when considering the design performances for a typical PI centralized controller. The study also looks at the impact of the zones number on the Control/WSAN performances.

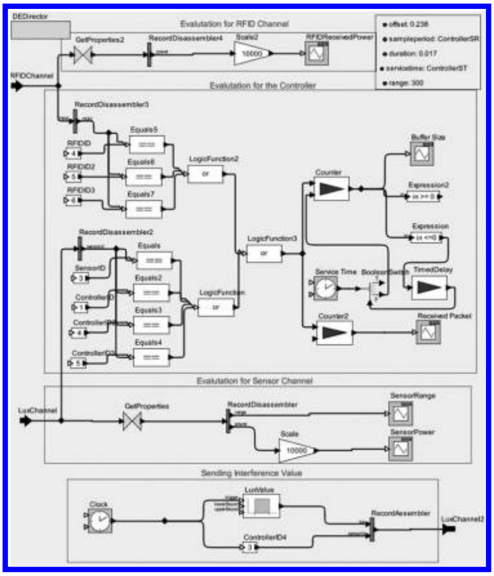

Figure 7. Controller/Receiver model.

We note that the PPD-Controller imposes some constraints that help to restrain the evaluation space; for example, a design constraints should be defined in order to determine the value of *CSP* that corresponds to each *SSP*. Mainly, the *CSP* is used to exchange the actuation values, so that the controller can detect the interference coming from other zones. Therfore, the controller changes its actuation value only when it receives a new sensed value from the sensor, i.e. CSP ≥ SSP. In this experimintal design, we consider the worst case from the WSAN side, i.e. CSP ≡ SSP.

4.1 *Control refinement*

In order to evaluate the control performance, the MSE between the sensed value and the set-point is used as follows.

$$MSE = \sum_{a=1}^{N} \frac{\sum_{k=1}^{M} (U_a(k) - S_a(k))^2}{M.N} \tag{2}$$

Where: N is the total number of zones; M is the total number of samples.

In relation to the *SSP* values and the corresponding *CSP*, we have considered typical set of values: {1, 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60}. For the zone number, *ZN* varies from one single zone to the maximum number of zones considered in the design specification (i.e. 10), $ZN \subset \{1, 2, 4, 8, 10\}$.

Figure 8 shows the control evaluation for each parameter. The satisfaction range for *SSP* and

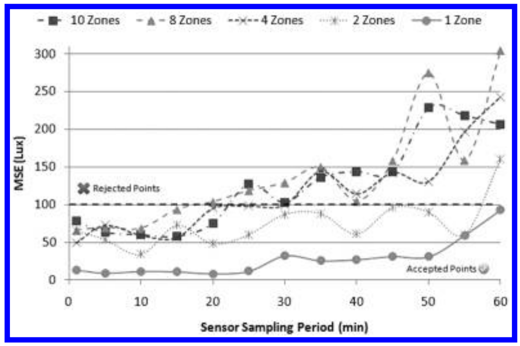

Figure 8. PPD control evaluation.

Table 1. $P_i(j)$ ranges at control refinement stage.

	$[a_i, b_i]$ (min)
PPD (NZ = 1)	[1,60]
PPD (NZ = 2)	[1,55]
PPD (NZ = 4)	[1,30]
PPD (NZ = 8)	[1,15]
PPD (NZ = 10)	[1,20]
PI-Centralized (10-zones)	[5]

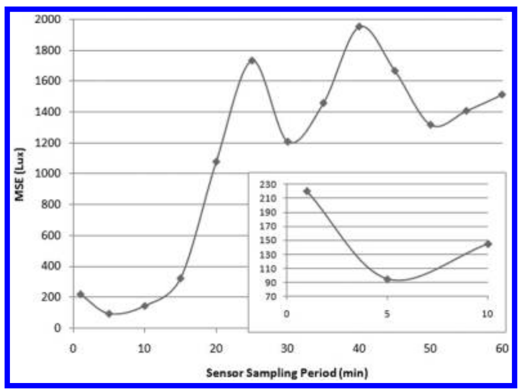

Figure 9. PI control evaluation.

CSP is determined by the boundaries shown in Table 1. In this case, we have assumed a threshold dominance of 100 Lux for the MSE.

Figure 9 shows the experimental results for a typical centralized PI controller controlling the lighting system for 10 zones. By assuming the same threshold dominance used previously, the satisfaction point for *SSP* equals 5 min (Table 1). Therefore, the PPD design offers a wider range for the SSP, which can reach 20 min, compared to the centralized option. This will certainly lead to better WSAN design.

Table 2. WSAN refinement stage.

	RFSP (sec)
PPD (NZ = 1)	2.5
PPD (NZ = 2)	2.5
PPD (NZ = 4)	3
PPD (NZ = 8)	3
PPD (NZ = 10)	3
PI-Centralized (10-zones)	15

We note that the wavy shape appearing in some ranges (Figures 8, 9) is due to the acceptable variation margin that equals to one dimming level in the PI-Controller (70 Lux).

4.2 *WSAN refinement*

After identifying the satisfactory range resulting from the previous step, the WSAN design is refined in order to reach the optimal QoS.

As mentioned earlier, our aim is to provide an optimum Control/WSAN co-design that maintain the maximum user comfort. To achieve this, the best WSAN QoS candidate is the Network Response Time (NRT). In our wireless network model, we have assumed that there is no packet drop, which means that the response time at the controller equals to the buffered packet multiplied by the controller service time (0.5 sec).

Large *SSP* values result in better WSAN performance and longer battery life. On the other hand, large *SSP* values do not affect the *NRT* and the user comfort, since it is within the optimal range. Therefore, we have considered the upper limit for each parameter.

As mentioned earlier, some parameters affect only the WSAN, which is the case for the sampling period of the RFID (*RFSP*). Therefore, we vary *RFSP* under an accepted stopping criteria (e.g. $NRT = 1$ sec).

Table 2 shows the experimental results for the different WSAN models and the corresponding *RFSP*. Through studying Table 2, we can conclude that in the centralized control strategy you have to accept slow response in the person movement update which may lead to user discomfort, as the user needs to wait for 15 sec to get his preference. However in the PPD control strategy, he needs to wait a maximum of 3 sec.

5 CONCLUSION

In this article, we have provided through our hybrid/multi-agent platform a refinement methodology for improving the Control/WSAN performance within the building automation domain. Such improvement plays a key role in guaranteeing properties such as safety, accuracy, stability and reactiveness, which greatly impact user comfort. The developed methodology can configure the Control/WSAN-correlated parameters, and thereby reach an efficient configuration. The approach has been tested on a PPD-Controller and PI centralized controller used for lighting systems. The impact of changing the correlated parameters on both control performance and the WSAN QoS has been considered, where priority is given to the objectives of the application, as represented in the control requirements.

As future work, we intend to apply our methodology to Heating, Ventilating, and Air Conditioning (HVAC) system, as this presents more interesting challenges in relation to user comfort and control stability. We also aim to deploy a demonstration of the developed system in the Environmental Research Institute building (ERI), which is the ITOBO Living Laboratory (Environmental Research Institute). The benefit of cross-layer modelling for distributed control constitutes an important research topic that we also intend to pursue in future work.

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A constraint-based intelligent controller for lighting systems

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ABSTRACT: A major factor in energy wastage in retail and public-office buildings is the inefficient control of lighting systems. This paper presents a constraint based optimiser for lighting control which minimises energy usage while maintaining occupant satisfaction. This controller is coupled with a reactive controller which we simulate using a hybrid/multi-agent platform. We apply this control strategy to a simulated open office scenario, and outline the simulation results and potential energy savings of the proposed strategy.

1 INTRODUCTION

A major source of energy inefficiency in buildings is suboptimal control. Lighting is one of the main energy consumers in buildings, responsible for 20% of total energy usage in US commercial buildings (EIA, 2003). Up to 58% of this may be wasted due to inefficient lighting control (Delaney, D.T. et al. 2009). The aim of our research is to define an intelligent control methodology which will optimise the light actuation levels to minimise energy wastage.

In this paper, we consider a two step approach, with a higher level controller periodically optimising initial settings, combined with a lower-level reactive controller actuating the light. There is existing work on both centralised optimisation (Singhvi, V. et al. 2005, Mahdavi, A. 2008) and combining decision support with existing control systems (Davidsson, P. et al. 2000, Boman, M. et al. 1999). We formulate the higher-level problem as constraint optimisation. We use hybrid systems models to model and simulate the building environment and reactive controller, to represent both the discrete and continuous components required in lighting control and presence sensing.

We assume a tracking system which monitors the location of individual occupants within the controlled area, and an interface which allows them to express preferences over the lighting. When significant changes occur in the environment, the constraint based optimiser computes initial actuator settings which minimise an objective function combining preferences and energy. The reactive controller then maintains the desired illuminance levels by actuating window blinds and internal lights to compensate for changes in the external light level.

The remainder of the paper is organised as follows: Section 2 introduces the reactive and optimising controllers and the process by which they share control. In Section 3 we specify the scenario and the reactive control strategy. Section 4 details the constraint based optimising controller. Section 5 briefly outlines the modelling methodology used in the simulated scenario and the results of that simulation. We conclude the paper in Section 6.

2 REACTIVE AND OPTIMISED CONTROL

To allow for both optimised and reactive control our approach uses two separate controllers which work together. In this section we describe their operation.

2.1 *Controller algorithm*

The actuators in the simulated environment are controlled directly by the simulated reactive controller. This controller starts by actuating initial light settings provided by the optimising controller, the 'initial configuration'. The optimising controller provides both the optimal actuator settings and the predicted resulting sensed illuminance levels. It is assumed that any small changes to the environment, such as changes in daylight levels, will result in small changes to the configuration, and thus only small changes to the objective value. If, for instance, daylight increases gradually, the lighting nearest the window merely need to be reduced slightly. Thus by progressivly altering the initial configuration to maintain the predicted levels, the reactive controller alone can maintain

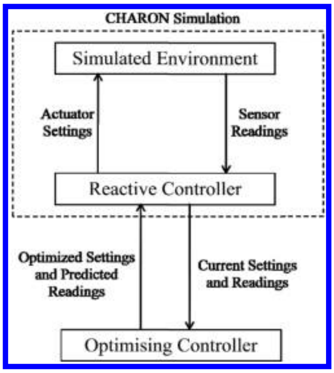

Figure 1. Control system.

an near-optimal configuration when small changes occur.

However, there may be circumstances in which the new optimal configuration is no longer in the neighbourhood of the current configuration, and cannot be found through reactive control alone. In our model two such circumstances exist: the movement of an occupant or significant drift from the initial configuration due to continued changes in the external light. In the case of an occupant moving the distribution of preferences across the environment will change, altering the preferred illuminance levels in a way the reactive controller cannot predict. In the case of configuration drift, we refer to small but cumulative changes to the external lighting of the environment causing the reactive controller's configuration to become increasingly distant from the initial configuration. When the initial configuration is modified beyond a certain margin, it is assumed that the external lighting may have changed sufficiently to move the optimal configuration out of the neighbourhood of the initial configuration. In both of the above circumstances the reactive controller requests a new configuration from the optimising controller.

The reactive controller includes the current actuator settings, sensor readings and occupant locations in its request for a new configuration. The optimising controller uses these and the stored occupant preferences to compute the optimal configuration according to the objective function. It then returns this configuration, including both the optimal actuator settings and predicted sensed illuminance levels, to the reactive controller. This is the new 'initial configuration', which the reactive controller implements and controls around as before.

2.2 *Model assumptions*

The simulation is an approximation of the scenario environment. We currently make some assumptions about the hardware and the propagation of light within the environment, as follows.

We assume that the propagation of light within the model is uniform and diffuse. The light received at any point from any source depends only on the distance between the point and the source. Similarly, blinding is assumed to uniformly decrease the amount of daylight entering the environment. With regard to the actuators and sensors, they function in an ideal fashion; the actuators emit exactly the amount of light that they are supposed to, and sensors always correctly report the exact illuminance level at their location. Furthermore, it is assumed that these devices are perfectly reliable, that they never suffer from control failures of any kind.

Future work will involve removing these assumptions from the model. Daylight entering the environment and the reduction of daylight via blinding is typically not uniform or diffuse. To account for this, the controller will need a model which can incorporate localised light and dark spots. The possibility of imprecise output from the actuators or inaccurate readings from the sensors adds uncertainty into the selection of the optimal configuration. The optimiser will have to account for the fact that its knowledge of the current configuration may be inaccurate, and that the suggested configuration may not have exactly the predicted effect, and choose the solution most likely to minimise the objective function. Control failure of actuators or sensors could change the options available to the controller, and so it will have to be able to detect such problems to avoid suggesting configurations which cannot actually be implemented.

3 INTELLIGENT LIGHTING SYSTEM SCENARIO

In this section we specify the scenario we are simulating and the reactive controller which controls the actuators.

3.1 *Scenario specification*

We have adopted a typical architecture as shown in Figure 2. We focus on an open office area, which contains 6 controlled zones, where each zone contains one artificial light and one light sensor. One Radio-Frequency Identification (RFID) receiver is used to cover the whole area; there is one window/binding in the left border of the considered area and a fix number of predefined occupant positions.

For the lighting model we integrate blinding and lighting controls. In order to enhance the efficiency of the resulting control model, an optimising controller has been implemented, as explained later.

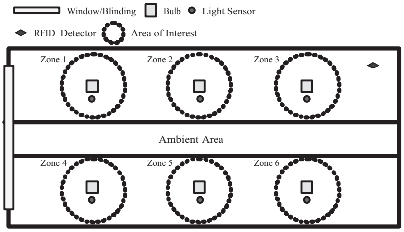

Figure 2. Scenario model specification.

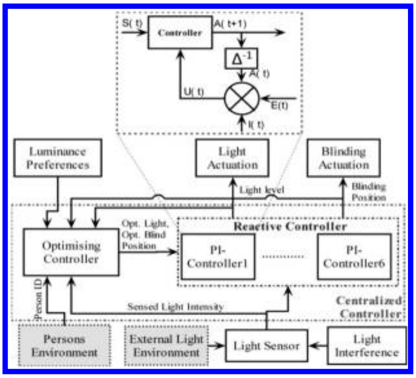

Figure 3. Control model.

As a summary, the lighting control scenario behaves as follows:

1. The user can switch on/off the automatic lighting system for several zones, or for all the system through a technician.
2. The occupants provide their light luminance preferences.
3. An occupant is tracked in each zone using RFID, and his preferences are considered wherever he is located.
4. The optimising controller receives the user preferences and sends back the optimal settings.
5. The reactive controller controls the artificial light and the blinding actuators in order to reach the optimal settings and to respond to the influence of changes in the daylight luminance.

3.2 *Reactive control strategy*

Figure 3 shows the agents of the control model and its interactions with the environment agents. The controller follows the following scenario in order to control the light intensity:

1. The optimising controller receives the user preferences for each person and its position, sends the optimal light setting and blinding position back to the reactive controller in order to refine the actuation values using a PI-Controller.
2. The reactive controller actuates the artificial light and the blinding position accordingly, then goes to 1 if the occupant preferences have been altered by the movement of an occupant or if a significant deviation from the optimised configuration has occurred.

The PI-Controller is used to predict the next actuation setting for the lighting dimming level in a close loop fashion (Kolokotsa, D. et al. 2009). The PI-Controller has two main status, first is unstable when the difference between the sensed light intensity and the optimal one is greater than 70 Lux (one light actuation level), and secondly, is stable, if the difference is less than or equal to 70 Lux.

4 CONSTRAINT BASED OPTIMISATION

The optimising controller is responsible for computing on request settings for the actuators which optimise both energy consumption and occupant satisfaction. To this end we model the energy cost and the effect on the building environment of the actuators, and the preferences of the occupants, as a Constraint Optimisation Problem (Dechter, R. 2003). A constraint problem consists of a set of variables, a domain of possible values for each variable, a set of constraints over the assignment of values to variables which restrict the values that may be assigned simultaneously, and an objective function over the assignments. A solution is an assignment of one value to each variable such that no constraint is violated. An optimal solution is one with the highest objective value. Solutions may be obtained by any suitable method, including backtracking and logical reasoning, mathematical programming, or local search.

4.1 *Preference modelling*

To quantify occupant satisfaction with a configuration we must model their preferences over illuminance levels. We model each occupant's preferences as a preference curve, which associates a satisfaction level from 0 to 1 with each possible lux level. These satisfaction levels may be derived from direct occupant feedback or learned over time based on their actions with regard to the lighting. The preference curves in our simulated scenario peak in the range of 400–500 lux, falling off to 0 satisfaction within 300 lux above or below that range.

Modelling an occupant's preferences over the entire range of illuminance levels allows us to determine an acceptable range of illuminance levels for that occupant. By constraining the occupant's satisfaction to be above a certain threshold, we compute a range of illuminance values within which the occupant is simply considered satisfied, and thus within which the energy cost component of the objective function will be the deciding factor. Since we model the occupant's preferences across all values, this satisfactory range is determined by the occupant's own sensitivity to different lighting conditions.

To apply these preferences to the physical environment, we break it down into control zones, each of which contains a set of zero or more occupants. The zone is the smallest unit of the environment which the controller reasons over, so preference curves are grouped into these zones. By averaging the preference curves of the relevant set of occupants, we produce a zone preference curve, which describes the overall satisfaction of that set of occupants.

Conflicts in occupant preferences may make it impossible to completely satisfy every occupant in a set. Thus the controller first determines the maximum achievable satisfaction for the set of occupants, and the satisfaction threshold is offset from this value.

4.2 *Actuation modelling*

We evaluate actuation in terms of the energy cost of the actuator configuration and occupant satisfaction with the resulting illuminance levels. The energy cost of each actuator is simply a direct function of that actuator's set point. However occupant satisfaction depends on the lighting conditions effected by the actuators, which is dependent on the combined effects of all the actuators. Thus, as with the preference model, we model the building environment as a set of zones, and model the effects the actuators have on that set of zones.

We model each actuator as a set point variable and a set of constraints which describe their energy cost and lighting effect. These set point variables are the decision variables of the constraint problem, the variables to which we assign values when searching for a solution. In our simulated scenario there are six lights and one blind. The lights have 11 possible set points ranging from 0 to 10, while the blind has 5 set points, from 0 to 4. In this model both the energy cost and light output are proportional to the set point.

For each actuator a set of constraints relate the output of that actuator to the lux of each zone which it affects. The illuminance received by a zone from each actuator is proportional to the base output of that actuator and is modeled as a relational constraint. The total lux in each zone is the sum of the individual contributions. These predicted lux values are the dependant variables of the model, and are evaluated against the occupants preferences as part of the objective function.

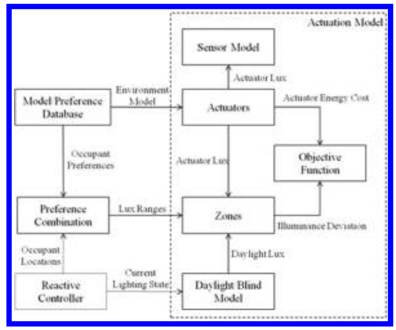

Figure 4. Optimising controller overview.

The objective value of a solution is the weighted sum of the total energy cost and total deviation from occupants' preferred lux level ranges. The total energy cost is the sum of the energy costs of all actuators. The total deviation is the sum across all zones of the distance of the predicted lux level from the preferred lux level range.

The blinding actuator is a special case which integrates both the effect of daylight on the environment and the effect of blinding on the daylight. The daylight entering the environment is treated as the base output of the blinding actuator, and it is assumed to have no energy cost. The level of daylight is determined using the actuator settings and sensor readings supplied by the reactive controller when the optimising controller is invoked. Any light which is not accounted for by the settings of the internal lights is assumed to be daylight.

We model the sensors in the environment in the same manner that we model zones. When we have determined the optimal configuration, we compute the illuminance levels the sensors should report when that configuration is implemented. These illuminance values are passed to the reactive controller, allowing it to control around the target illuminance levels as well as simply implementing the actuator set points it is given.

Figure 4 shows the complete actuation model, including the external data sources. When the model is instantiated we search through the space of possible assignments to find the one which minimises the objective function. We do this using backtracking search interleaved with constraint propagation, using the min-dom and min-value heuristics. The model is implemented in and solved with CP-Inside (Feldman, J. & Freuder, E. 2009). We find the optimal solution in, on average, 250 milliseconds.

5 SIMULATION

The control system and its environment have been modelled and simulated using the Charon simulation tool-set (Charon). In this section we briefly describe the simulation models and discuss the results including power savings comparing to a typical control technique used in building automation.

5.1 *Modelling for simulation*

In order to model the system, two types of agent have been used: Control- and Environment Agents. The behaviour of each agent is described using a hierarchy of modes.

Regarding the Control Agents, one main agent is used for the reactive controller, such that one subagent is used to refine the actuation values in each zone using a PI-Controller as depicted in Figure 5. Another agent is used to call the optimising controller. This agent is triggered whenever the user preferences change or a significant change in the actuator configuration occurs. Finally, the sensor agent is used to update the internal light value every sampling period, based on the actuation value, the light interference and the daylight light coming to the sensor. It considers an intensity attenuation factor of $1/r^2$, where r is the distance from the light source to the sensor.

For the Environment Agents, three Charon agents have been used to model Person Movements, Daylight Intensity and Window Blinding Occlusion.

Due to space limitation we only show one of the control modes depicted in Figure 5.

5.2 *Simulation results*

To provide an overview of the control strategy and resulting lighting conditions in the office we show Figures 6a–6d. Figure 6a shows the locations of the occupants by zone, with zone 0 referring to occupants who are not present. Figure 6b shows the computed optimal light levels to be achieved by the reactive controller, while Figure 6c shows the actual sensed light levels. These levels differ due to changes made by the reactive controller to respond to the values in Figure 6d, the progression of daylight over the course of the simulated day.

To highlight the effects of the control strategy we consider zones 1, 3 and 6. Zone 1 is adjacent to the window and is thus heavily influenced by daylight. Due to this a pattern of decreases and increases in the internal light level of Zone 1 can be seen as the reactive controller corrects for the loss of daylight towards the end of the day. Shortly thereafter another occupant enters the zone, causing a small increase in the optimal light level, and a corresponding increase in the actual light level as the reactive controller implements the new optimised solution. Zone 6 is seen to have a more stable light level and

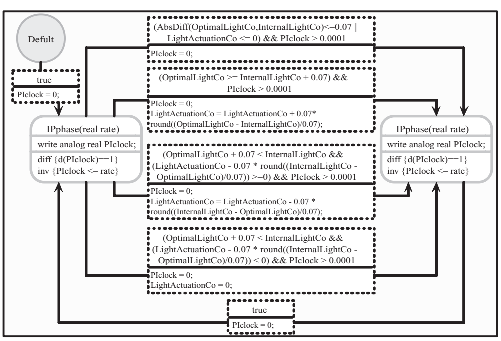

Figure 5. PI-Controller.

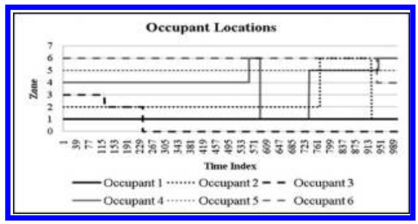

Figure 6a. Occupant locations.

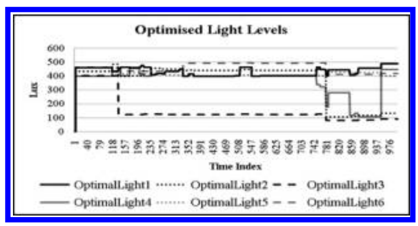

Figure 6b. Optimised light levels.

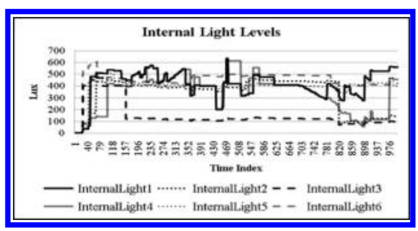

Figure 6c. Internal light levels.

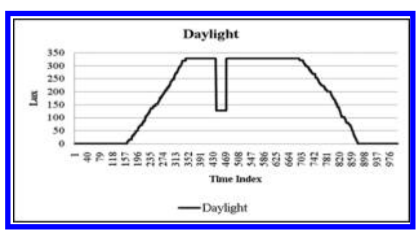

Figure 6d. Daylight.

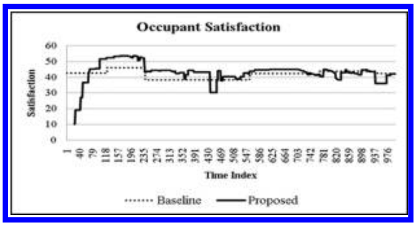

Figure 6e. Occupant satisfaction.

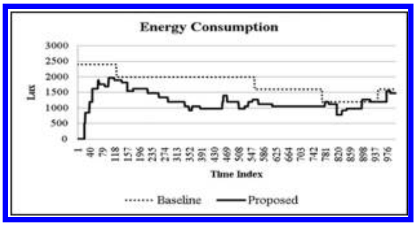

Figure 6f. Energy consumption.

more closely follow the optimal light level as it is further from the window. Zone 3 maintains a low but nonzero optimal light level despite being unoccupied most of the day. This is due to the optimised light levels being predicted sensor readings, which take into account the effects of all actuators.

To evaluate the potential energy savings and effects on occupant satisfaction of our proposed strategy, we compare the performance of our controller against a base line control system. This base line is a typical reactive control strategy used in building automation. We assume a passive infrared sensor for presence detection, with the light in each zone switching on to a predefined level whenever at least 1 occupant is in that zone. We consider 400 lux to be the optimal lux level for this strategy, as it has the capacity to satisfy the occupants under all conditions without undue energy use.

Figure 6e compares the actual occupant satisfaction level against that which would be achieved by the base line system. Sudden changes in actual satisfaction occur as there is a small delay between the movement of an occupant and the reaction of the controller. Note, though, that this effect is magnified in the results, since the simulation is running approx. 350 times faster than real time. In practice, the delay is never more than 1 second. These delays are also responsible for the unstable data prior to time index 118, which we disregard when evaluating energy performance below. These delays notwithstanding, our controller maintains occupant satisfaction at or above the base line.

Figure 6f shows energy consumption in terms of lux as energy consumption scales linearly with actuator output. The results show a 30% energy saving over the base line strategy.

6 CONCLUSION

We have proposed a constraint based optimiser and control strategy for an intelligent automated lighting system. The system uses supplied occupant preference data and a tracking system to maintain occupant satisfaction while optimising energy use. Simulation results show that the proposed strategy reduces energy consumption by around 30% compared to a standard base line approach while maintaining occupant satisfaction at high levels. Our current model makes a number of assumptions about the environment and hardware; future work will be to remove these assumptions and find solutions to the resulting challenges.

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Comparison of diagnostics granularity for lighting control systems

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ABSTRACT: Intelligent buildings are complex systems consisting of embedded computation, technical devices, (inter) acting users and physical quantities. Integrating such different aspects brings together subsystems that must be represented differently. Automated problem-solving on the other side is based on models that capture the essential aspects of the behavior in a uniform way. Here we focus on diagnostics for intelligent buildings, and in particular the automated generation of diagnostics from design models for buildings. In particular, we extend previous work on diagnostics generation in two ways: (1) Defining a meta-model for a specific domain, as illustrated through the lighting control domain, allows us to fully automate the diagnostics generation process. (2) We propose a methodology that allows the system engineer to adjust and compare levels of granularity of the diagnosis according to a specific diagnosis task.

1 INTRODUCTION

1.1 *Motivation*

Given the importance of minimizing energy use in building applications, researchers are studying the role of many tools for such purposes. One tool, diagnostics, plays a key role in energy optimisation and user comfort in buildings by identifying sub-optimal energy use caused by component faults.

Our work has addressed how to use detailed building systems models (such as energy simulation models) as the basis for automatically generating embeddable diagnostics code. In [Behrens, 2010] we showed how we can semi-automatically generate discrete propositional logic models Φ_D for diagnostics from a hybrid systems model, *HS*. We showed how to use a model-transformation approach to first abstract the *HS* model into a simpler discrete model, from which we generate propositional logic sentences.

In our work, we examine the *diagnosis task* of finding a representation of the system that is capable of isolating severe system faults while reducing false alarms. Defining such a diagnosis task includes analysis of the severity of faults. The *complexity* of a *HS* model is associated with the number of discrete states, the number of continuous state variables, and the type of equations defining continuous state-evolution [Mazzi, 2008]; the corresponding diagnosis model Φ_D will have lower complexity than HS, since there are only discrete states in Φ_D.

Fault-isolation using detailed models in on-board applications is resource-consuming, and models must be abstracted in order to compute diagnostics in real time. The challenge is to reduce the complexity of Φ_D such that we can still accomplish the diagnosis task.

Granularity is the extent to which abstraction breaks down a system into smaller parts. The complexity of an abstracted model is a result of the granularity of the abstraction function ξ. In general, fine granularity leads to high complexity whereas coarse granularity results in a model of lower complexity.

Finding the right granularity of abstraction for a system in order to fulfill the diagnosis task at lowest possible complexity is challenging [Darwiche, 2000]. In this paper we compare diagnosis models of different granularity, to show the types of faults that can be captured by the different granularity levels. We use a set of lighting system models as the application domain.

In summary, our contributions are:

1. We propose a meta-model for lighting systems in buildings from which diagnostics at different granularity can be automatically generated.
2. We outline how four different abstraction functions bring forth diagnostics of different granularity and complexity.
3. We compare the different reduced-order models in terms of complexity and how they fulfill the diagnosis task given.

The rest of this paper is organized as follows: We introduce our framework and the main technologies in section 2. Preliminaries that deal with model abstraction are briefly given in section 3, and the methodology of our diagnostics comparison is described in section 4. In section 5 we illustrate our achievements through a detailed example. Section 6 concludes our work and gives an outlook onto our future contributions.

1.2 *Related work*

We summarize related work in two areas, model abstraction and auto-generated diagnostics.

Concepts of model abstraction have been widely discussed in the literature [Krantz, 1995], [Cousot, 2000], whereas ideas of adjusting abstraction to a specific "task" are relatively new [Sachenbacher, 2004]. The application to building automation behavioral models is novel.

Our research work concerns the auto-generation of diagnostics. The approach we propose is different from most existing approaches, which generate models from diagnosis components rather than abstract a diagnosis model from more complex behavior models. Among this class of approaches, we examine one particular paper. [Dressler, 2002] describes a methodology of diagnostics generation for car subsystems, based on the assumption that models of car systems can be automatically composed from model libraries.

2 ARCHITECTURE

2.1 *Global framework*

Within the development of auto-generation of diagnostics for building automation systems, one of the main difficulties is to tap resources from which diagnostics models can be transformed. Building Information Modelling (BIM) involves integration of CAD drawings, geospatial data and other graphical and non-graphical data. It serves as a shared source of information on a building. Yet, behavioral aspects are rarely modeled and the Industry Foundation Classes (IFC), the standard interchange format for building models, support for smart objects is limited [Halfawy, 2002].

We assume that a given BIM application provides a model that describes detailed information about components of control systems, i.e., types of sensors, actuators and control strategies and component interconnectivity. Further, we assume a library that provides us with behavioural models associated with the components. Based on these assumptions, we have built our framework, which uses a global source model to combine the spatial data and interconnectivity extracted from the BIM application with behaviours extracted from the library of behaviour models. Figure 1 illustrates

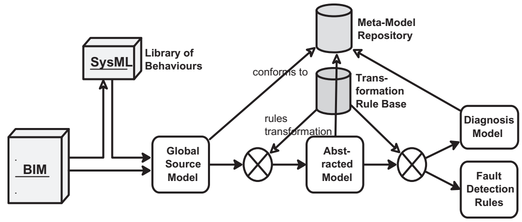

Figure 1. Global framework.

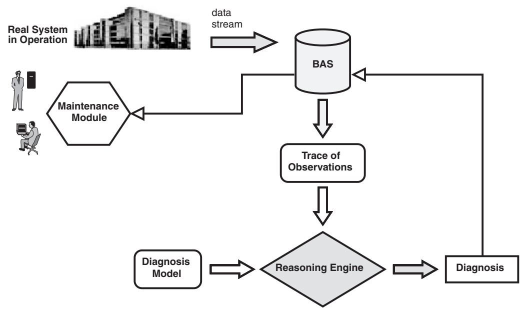

Figure 2. Model-based diagnostics in building automation.

the global architecture of the framework: This global source model is transformed, using appropriate meta-models and transformation rules, into a model for model-based diagnostics.

2.2 *Model-based diagnostics*

Fault diagnosis is the process of analyzing abnormal system behavior in order to identify and localize the components that are the root cause of a failure. Compared to rule-based diagnostics, which associates sets of if-then rules to certain malfunctions, Model-Based Diagnostics (MBD) uses forward models of systems and then applies diagnostics algorithms on these to decide whether a certain behavior is normal or abnormal [Darwiche].

Figure 2 illustrates how diagnostics is embedded in our framework for fault detection and diagnosis of building automation. The reasoning engine compares the observed values with the predicted state of the system. In case of a conflict the reasoning engine provides the most possible affected component(s) as diagnosis output to be forwarded to a maintenance module.

Although MBD has the capability to isolate more diagnoses than rule-based approaches, it faces the challenge of defining the appropriate MBD models. Typically, diagnostics are generated independent of the design process. In our work, we assume that we can use design models to automate the process of diagnostics, and we apply a model-transformation approach to the diagnostics, using design models to auto-generate the MBD models.

A second drawback of MBD is the complexity of its models and inference, as compared to rules. Hence, it is important to use MBD models (in embedded-systems applications) that provide a good tradeoff of fault-isolation capabilities for memory and CPU requirements.

2.3 *Model transformation*

We have two applications, a source and a target application, with a corresponding meta-model for each application. We use the theory of model transformation [Mens, 2006] to formalize our transformation process in terms of a rewrite procedure. Model transformations that translate a source model into an output model can be expressed in the form of rewriting rules. According to Mens et al. [Mens, 2006], the transformation we adopt is an exogenous transformation, in that the source and target model are expressed in different languages, i.e., behaviour models represented as FSM or hybrid automata and propositional logic languages.

3 QUALITATIVE ABSTRACTION

3.1 *Preliminaries*

Abstraction is the process of separating essential information from details, focusing on the former while ignoring the latter. An *abstraction function* maps a model M into a model M′ of lower complexity. Any abstraction entails a loss of information. Therefore, not all questions can be answered through the abstracted model; hence, in our application not all faults can be diagnosed precisely through the resulting diagnostics model. The diagnosability of the abstract model depends on the type, granularity and coordination of the abstraction method.

In this section we analyze the methods of domain abstraction and function abstraction, and evaluate the granularity of different aspects using the diagnostics of a lighting control system.

3.2 *Domain abstraction*

A domain abstraction maps values of a domain $dom_1(v)$ to a domain $dom_2(v)$ that is an ordered set of intervals taken from dom_1. Sachenbacher et al. [Sachenbacher, 2005] define an observable distinction that is the granularity of the observable variables and a target distinction that is the granularity of the solution of the diagnosis problem. They further describe the "goal of task-dependant qualitative domain abstraction is to determine maximal partitions for the variables' domains […] that retain all the necessary distinctions".

Definition. *(Domain Abstraction Function) Given a continuous domain $dom_c(v_i)$ for a variable v_i and an ordered set of landmarks $L(v_i) = \{l_1, l_2, \dots, l_n\}$ associated with v_i the domain abstraction function ξ_{dom} provides the abstracted discrete domain $dom_d = \xi_{dom}(dom_c, L, Y(L))$ where $Y(L)$ assigns one of the values $\{b, o, a\}$ to each landmark l_i indicating whether l_i is included in the interval below, forms an own interval $[l_i, l_i]$ or is included in the above interval.*

Definition. *(Granularity of Domain Abstraction) The granularity of the domain abstraction $g(\xi_{dom})$ is the number of intervals in which a domain $dom_c(v_i)$ is split by a given a bstraction function ξ_{dom}.*

Remark. It is obvious that $n - 1 \leq g(\xi_{dom}) \leq 2n + 1$ for $n = |L|$.

3.3 *Function abstraction*

Abstraction of a function *f* includes rewriting the continuous input and/or output to a representation that maps discrete arguments to discrete values. We define two different types of function abstraction:

1. We represent *f* through discrete directions in which the value changes: increase, decrease, hold and jump-to. The output can then be modeled as a separate automaton.
2. We represent the *f* by tracking its value. The number of discrete states of the system must therefore be multiplied by the granularity of the abstracted output domain.

We call (1) the *local function abstraction* because functions are replaced through additional states and transitions within the same component; and we call (2) the *global function abstraction* in which the functions are replaced through states and transitions in an additional component changing the global structure of the model.

Definition. *(Granularity of Function Abstraction) The granularity of the function abstraction $g(\xi_{fun})$ is the number of transitions between states that were created by the abstraction function ξ_{fun} in order to represent f.*

Remark. Given n possible output values for a function *f*, the granularity of the abstracted representation $g(\xi_{fun})$ is $n \leq g(\xi_{fun}) \leq n^2$ for both abstraction types.

3.4 *Combined abstraction*

Assuming a variable *v* that is the state/output variable q_i of a component C_i and that is forwarded as input y_j to a component C_j, in the ideal case the landmarks $L(v) = \{l_1, l_2, \ldots, l_n\}$ are the same in C_i and C_j. However, if this is not the case, abstraction functions must be composed.

We outline two methods of composition:

1. Abstracting domains $dom_c(q_i)$ and $dom_c(y_j)$ with different abstraction functions and then provide a mapping function from q_i to y_j, that is from the discrete domain $dom_d(q_i)$ to the discrete domain $dom_d(y_j)$.
2. Combining the abstraction functions $\xi(q_i)$ and $\xi(y_j)$ by either adding their granularities in case of domain abstraction of multiplying their granularities in case of function abstraction.

Definition. *(Granularity of Abstraction) Given an Abstraction A of a model M, the granularity of the abstraction is the pair of the granularity of the domain abstraction and the granularity of the function abstraction* $g(A) = (g(\xi_{dom}), g(\xi_{fun}))$.

4 METHODOLOGY OF DIAGNOSTICS COMPARISON

A diagnosis problem arises when some symptoms are observed, that is, when the system's actual behaviour is in contradiction with the expected behaviour. We adopt definitions from [Provan, 2009] for propositional diagnosis mode, observation and diagnosis:

Definition. *(Propositional Diagnosis Model) A discrete diagnosis model is specified by a tuple* $\Phi_D = \{I, V, E, \Pi\}$ *where* $I \subset \aleph$ *is a temporal index; V is a set of discrete-values indexes by I, such that* $V_f \subset V$ *is the set of failure mode variables, and* $V_O \subset V$ *is the set of observable variables;* $E \subseteq V_f \times \mathcal{L}_n$ *consists of propositional equations (where* $\mathcal{L}_n$ *is a propositional well-formed formula over* (V/V_f)*; and Π is a discrete probability distribution over the equations and/or variables.*

Definition. *(Observation) An observation α is an instantiation of the set of observable variables* V_O.

Definition. *(Diagnosis) Given a diagnostic model* $\Phi_D = \{I, V, E, \Pi\}$, *diagnosis δ is an assignment to all failure mode variables* V_f *of the diagnostic system* Φ_D *such that* $\Phi_D \wedge \alpha \wedge \delta \mid\neq \perp$ *for an observation α.*

We further define the abstraction of a diagnosis is the pair of the abstraction of the model and the abstraction of the observation.

Definition. *(System Abstraction) Assuming a System S that is represented through a model* Φ_H *and instantiated with an observation α, an abstraction of S is the pair* $A_i = (M_i, O_i)$ *where* $M_i = \xi_i(\Phi_H)$ *is the abstraction of the propositional diagnosis model and* $O_i = \chi_i(\alpha)$ *is the abstraction of an observation.*

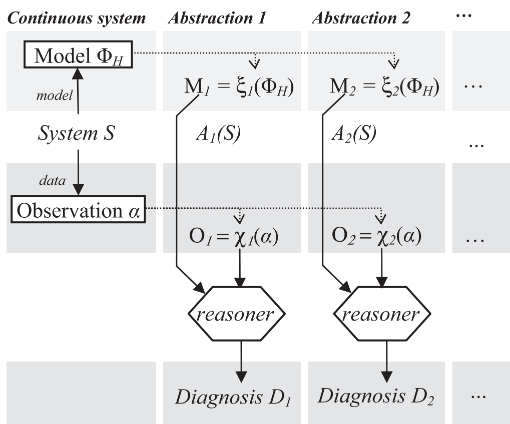

Figure 3. Methodology for abstraction granularity.

Remark. Φ_D in this definition is the abstracted model $M_k = \xi_k(\Phi_H)$ in case of highest possible granularity of the abstraction function ξ_k.

As shown in Fig. 3, different abstracted systems are constructed using different granularities. Each system is composed by the abstracted model and the corresponding observation. The diagnosability of the resulting systems is analyzed based on the granularity and the complexity of the abstraction function.

In the following section we will compare four abstractions of a typical lighting system in order to reason about their granularity, complexity and whether the diagnosis task is fulfilled.

5 EXAMPLE

5.1 *Lighting system model*

We illustrate our approach through a simple example of a system that controls a lamp with four actuation levels in a zone that is also illuminated by natural (ambient) light. A light sensor and a presence sensor provide a numeric value for the combined light intensity and a truth-value for the occupancy as input parameters to the control unit. A model of such a system is depicted in Fig. 4.

The controller has four states $Q_{Ctrl} = \{\text{off, hold, decr, incr}\}$ to set the actuation level v_{ActL} within its domain $dom(v_{ActL}) = \{0, 1, 2, 3\}$. The input variables v_{CombL} and $v_{Occupancy}$ guard the transitions between the states in such way that off is activated to set $v_{ActL}' = 0$ under the condition that $v_{Occupancy} = false$. If $v_{Occupancy} = true$ and the light-level is within an optimal range $[\alpha, \beta]$, the controller enters or remains in state *hold* and does not change v_{ActL}. If $v_{Occupancy} = true$ and the light-level is not in an optimal

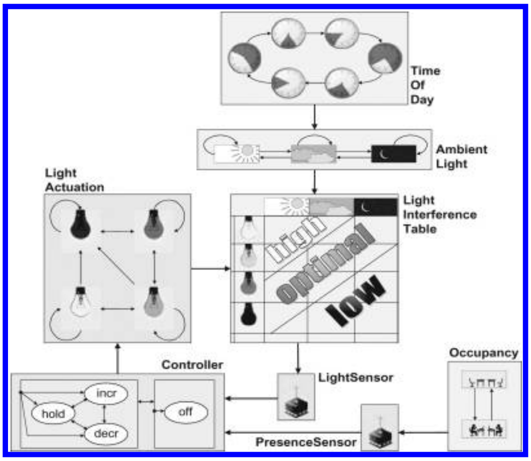

Figure 4. Typical lighting system.

Table 1. Interference table.

	Ambient light		
Actuation level	dark (<100 lx)	dawn (100–1000 lx)	bright (>1000 lx)
0 (0 lx)	0–90 lx	50–900 lx	>500 lx
1 (200 lx)	176–290 lx	226–1100 lx	>676 lx
2 (400 lx)	352–490 lx	402–1300 lx	>852 lx
3 (600 lx)	528–690 lx	578–1500 lx	>1028 lx

range, the controller can either decrease the actuation level step-wise or increase the actuation level "jump-wise". I.e., if $v_{LightL} > \beta$ the controller enters state decr with the function f_{decr}: $v_{ActL}' = v_{ActL} - 1$. If $v_{CombL} < \alpha$, then v_{ActL} is increased through the function f_{incr} (1) of the state incr:

$$v_{ActL}' = v_{ActL} + \left\lceil \frac{\alpha - v_{LightL}}{200} \right\rceil \quad (1)$$

Table 1 lists the combined light of the ambient and artificial light at the position where the light sensor is located. The artificial light directly depends on the actuation level that is discrete by its nature. There is no sensor to measure the intensity of the ambient light in the system; therefore it is estimated based on the time of day (and eventually astrological time).

For the purpose of the diagnosability analysis we construct trace tables that contain the system observations and the corresponding unobservable system parameters. The following tables describe the traces for the nominal behavior (Table 2) and behavior in case of a sensor fault (Table 3) and in case of an actuation fault (Table 4).

Table 2. Trace of the continuous model, nominal behavior.

t	7:10	7:15	7:16	7:25	…
v_{AmbL}	100 lx	120 lx	120 lx	250 lx	…
v_{CombL}	83 lx	97 lx	598 lx	705 lx	…
v_{CombL_S}	85 lx	95 lx	600 lx	705 lx	…
$v_{Occupancy}$	false	true	true	true	…
$v_{Occupancy\_S}$	false	true	true	true	…
q_{Ctrl}	off	incr	hold	decr	…
v_{actL}	0	3	3	2	…
v_{ArtL}	0 lx	600 lx	600 lx	400 lx	…

Table 3. Trace of the continuous model, sensor fault.

t	7:10	7:15	7:16	7:17	7:18	…
v_{AmbL}	100 lx	120 lx	120 lx	122 lx	122 lx	…
v_{CombL}	83 lx	97 lx	598 lx	98 lx	455 lx	…
v_{CombL_S}	85 lx	95 lx	**2000 lx**	100 lx	460 lx	…
$v_{Occupancy}$	false	true	true	true	true	…
$v_{Occupancy\_S}$	false	true	true	true	true	…
q_{Ctrl}	off	incr	decr	incr	incr	…
v_{actL}	0	3	0	2	3	…
v_{ArtL}	0 lx	600 lx	0 lx	400 lx	600 lx	…

Table 4. Trace of the continuous model, actuator/light fault.

t	7:10	7:15	7:16	7:17	7:18	…
v_{AmbL}	100 lx	120 lx	120 lx	122 lx	122 lx	…
v_{CombL}	83 lx	97 lx	97 lx	98 lx	98 lx	…
v_{CombL_S}	85 lx	95 lx	95 lx	100 lx	100 lx	…
$v_{Occupancy}$	false	true	true	true	true	…
$v_{Occupancy\_S}$	false	true	true	true	true	…
q_{Ctrl}	off	incr	incr	incr	incr	…
v_{actL}	0	3	3	3	3	…
v_{ArtL}	0 lx	**0 lx**	**0 lx**	**0 lx**	**0 lx**	…

5.2 *Abstractions*

As mentioned earlier, four abstractions have been calculated mainly driven by the domain of the combined light.

- The coarse domain abstraction (A_1) uses three intervals to determine the light level based on the optimal range that drives the controller.
- The fine domain abstraction has a finer granularity where the light level is represented by 15 intervals corresponding to the interference table. The composed domain abstraction (A_2), based on merging the landmarks of both the coarse and the fine domain abstraction, represents the domain of the light level by 16 intervals.
- The function abstraction of f_{incr} (A_3) combines a local function abstraction with corresponding domain abstraction of five intervals.

Table 5. Evaluation of four different abstractions.

	A_1	A_2	A_3	$A_4 = \Phi_D$
Nominal behavior	ok	ok	ok	ok
Faulty behavior sensor out of range	no	ok	no	ok
Faulty behavior broken actuator	3 steps	3 steps	1 step	1 step
Granularity $g(A) = (g(\xi_{dom}), g(\xi_{fun}))$	(3, 14)	(16, 14)	(5, 30)	(18, 30)
Complexity of diagnosis	low	medium	medium	high

- The finest possible abstraction ($A_4 = \Phi_D$) combines all the domain abstractions used above with the finer local function abstraction.

5.3 *Discussions*

Table 5 shows evaluations of the four abstractions of the lighting system model. Since all of the abstractions either match or extend the range of nominal behavior of the original model, no false alarms are raised, if undisturbed operation of the diagnosis framework is assured. The fault of a sensor reading being out of range (Table 3) is covered by those abstractions with the finer granularity of the domain abstraction for v_{CombL}, A_2 and A_4. A faulty actuator, i.e., a burnt-out bulb, (Table 4) is detected by all abstractions. However, only if we use the local abstraction function for f_{incr}, as in A_3 and A_4, can we detect the malfunction immediately. Using global abstraction, the actuation level v_{ActL} cannot be tracked, and the detection of faulty behaviors of the actuator takes as many observations as there are actuation levels above the current one.

6 CONCLUSION AND FUTURE WORK

The advantages of model-based diagnostics over state-of-the-art rule-based diagnostics increase with growing system complexity, because the number of possible fault combinations that explain an anomalous observation rises exponentially with the number of components. We showed that a model-transformation approach can generate model-based diagnostics using models defined for the design process. Through an example, we showed that different abstractions can be constructed using different granularities. We provided a methodology to construct and compare the abstracted systems where the diagnosability and the complexity of the granularity are analyzed. Using this approach, we can tailor the abstraction level to the required diagnosis-model granularity. This can help embed diagnostics code that satisfies the goal of isolating faults appropriately, while using the least amount of memory and CPU.

We plan to extend this work in a variety of ways, including: (1) extend the class of diagnosis models to incorporate explicit fault behaviors, rather than simply deviations from nominal behavior; (2) extend the class of source (reference) models to cover a wider range of control systems, sensors, actuators and physical environments found in building automation systems.

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Building maintenance scheduling using cost-based reasoning and constraint programming techniques

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ABSTRACT: Efficient scheduling of maintenance tasks in business or residential buildings is of significant importance on operation of buildings. Inadequate maintenance schedules could have serious consequences, including productivity losses due to failures of building components, safety hazards that might cost lives, or inefficient energy use. Other important considerations include running costs and dissatisfied occupants. Consequently, optimised maintenance scheduling is becoming a crucial requirement for building sustainability and reduction of operating costs. This paper presents a constraint based building maintenance scheduling tool that produces optimised weekly maintenance schedules taking into consideration a variety of constraints and multiple objectives. Additionally, we introduce our heuristic ModReg that uses cost reasoning to guide the search process towards an optimal schedule. Experimental evaluation demonstrates that our ModReg heuristic clearly outperforms the Dom/Wdeg heuristic and enables our maintenance scheduling tool to provide optimal schedules for large problem instances in a short period of time.

1 INTRODUCTION

Efficient building operation is challenged by conflicting objectives including building sustainability and the reduction of operating costs. Generally, buildings are complex systems that consist of many interconnected components. These components are subject to deteriorations that could lead to poor performance or failure. Malfunctioning building components could significantly increase energy consumption. For example, a defective sensor in a heater could lead to considerable energy losses. Similarly, a failure occurring in a building component might have a major impact on its performance or may lead to an immediate failure in other building components (e.g., a failure in a solar panel pump might result into total failure in the whole solar circuit). Hence, the optimisation of maintenance schedules could be significant for sustainable and economic building operation.

A schedule is an allocation of resources (e.g., engineers) and times to tasks. Generally, a maintenance task is either planned or reactive. The former corresponds to maintenance tasks carried out at predetermined time intervals to reduce the probability of failure or performance degradation of building components. The latter are maintenance tasks evolving in response to breakdowns or faults. Additionally, each task may have several constraints including time-related and resource-related constraints.

Typically, a maintenance schedule should satisfy a wide variety of constraints. For example, an engineer should be assigned one task at any time interval, commonly known as disjunctive constraint (Baptiste & Le Pape, 1995). Other constraints define inter-dependency relations between tasks including concurrency, precedence, and non-overlapping. Concurrency constraints may require a set of tasks to start at the same time, while precedence constraints ensure that one set of tasks concludes before another set starts. Non-overlapping constraints restrict a set of tasks from overlapping during their execution (e.g., due to safety reasons).

An optimised building maintenance schedule is one that satisfies all constraints while minimizing the associated operating costs including maintenance and energy costs. Energy costs are associated with delayed scheduling of maintenance for components consuming excess energy if they are faulty, while maintenance costs correspond to cost overheads as a result of scheduling tasks out of contracted working hours and as penalties may apply due to scheduling tasks beyond their response time windows. A response time window states when a task should be carried out according to a service level agreement (SLA). Typically, the SLA defines an expected minimal level of service and may specify financial penalties for the service provider in case the service falls below the minimal level, e.g., failing to address a serious failure in a timely manner.

In their general form, scheduling problems are NP-Hard (Graham, et al., 1977) (Garey & Johnson, 1979). Thus, much of the research effort focuses on solving scheduling problems efficiently. In this paper, we present a constraint based scheduling tool that computes optimised weekly maintenance schedules while accommodating the aforementioned constraint types. To the best of our knowledge, this tool represents the first attempt to solve building maintenance scheduling using constraint programming techniques. Additionally, we show the computational benefits of using our heuristic ModReg. Experimental evaluation shows that our ModReg heuristic significantly improves the performance of our maintenance scheduling tool and enables producing optimal schedules for large problem instances in a very short time.

The rest of this paper is organized as follows. Section 2 highlights related maintenance scheduling work and the technology used in solving our maintenance scheduling problem. Our constraint programming model is presented in Section 3. We describe our ModReg heuristic in Section 4 followed by Section 5 that provides experimental evaluation of the proposed heuristic. Finally, the paper concludes in Section 6 with a summary and an outline for future work.

2 BACKGROUND

2.1 *Related work*

In the area of maintenance scheduling, there are a number of works that solve these problems using several mathematical techniques, including Constraint Programming, Mixed Integer Linear Programming, Metaheuristics, and Hybrid methods that combine different techniques in order to gain their augmented advantages. For example, (Chun, et al., 2005) use Genetic Algorithms in scheduling maintenance works for the MTR Corporation subway in Hong Kong. Tabu Search is used in (Sawa, et al., 1999) to provide an automatic scheduling method for maintenance outage task of transmission and substation systems. Additionally, British telecommunications developed a dynamic scheduler that combines local search (i.e., Simulated Annealing) with constraint programming techniques to assign field engineers to different types of activities including customer service, network maintenance, and faults repair (Lesaint, et al., 1998).

The scheduling of maintenance activities for generation and transmission networks in power systems received significant attention in the literature. Many techniques have been applied to solve this problem including but not limited to Mixed Integer Linear Programming (Marwali & Shahidehpour, 1997), Dynamic Programming (Zurn & Quintana, 1975), Constraint Programming (Creemers, et al., 1995), Metaheuirstics (Langdon & Treleaven, 1997), and recently a hybrid constraint method that integrates a constraint programming model with a local search solving technique (Gomes, et al., 2007).

However, none of the above approaches can be used to solve building maintenance scheduling problems. The closest work to ours is the one described in (Ko, 2008). It presents a building maintenance system that uses RFID in maintenance management and includes a scheduling module. This module uses mathematical programming to schedule planned maintenance activities while minimizing the total maintenance time. The scheduling module, however, provides schedules for planned maintenance only. Additionally, no details are provided about problem modelling and handling of different constraints including restrictions of unary resources and temporal constraints.

2.2 *Constraint programming*

The building maintenance scheduling problem incorporates different types of constraints. Thus, the technology used should enable an easy and efficient representation for these constraints in addition to its flexibility in extending the constraint set. Based on these requirements, we use constraint programming in developing our maintenance scheduling tool. Constraint Programming (CP) is a powerful paradigm for solving combinatorial search problems and is applied successfully in many domains including planning, scheduling, vehicle routing, networks, and bio-informatics (Rossi, et al., 2006). A CP problem is composed of a finite set of variables, where each variable has a domain of possible values and constraints restricting combinations of values that variables can take simultaneously. The aim is to find either a feasible solution that provides a complete assignment of variables satisfying all the constraints, an optimal feasible solution (in case of optimisation) that minimizes or maximizes an objective function, or to prove the infeasibility of the problem, i.e. no solution could be obtained.

In CP, problems are solved with a combination of backtracking search and propagation of constraints. After each branching decision in the search, the logical consequences of the choice are propagated through the domains of as yet uninstantiated variables. This is normally handled by through filtering algorithms associated with the constraints, which rem ove from the domains any value that can no longer take part in any solution consistent with the current choices. If any domain is ever emptied, the current choices cannot be extended to a solution, and the search process backtracks, restoring values to domains as appropriate.

During constraint propagation, each constraint applies its own filtering locally over the included variables independent on the filtering applied by other constraints defined in the problem. Note that although constraint propagation reduces search space, it does not remove all infeasible values. The removal of all infeasible values from domains of variables is at least as hard as solving the problem. One way to improve the reasoning power of a CP solver is by using Global Constraints, which relies on efficient filtering algorithms that capture interesting substructures of a problem. Benefits of global constraints are twofold: allowing more filtering in comparison to a collection of primitive constraints and simplifying problem modelling, by providing an abstract level of constraint specification.

Typically, finding solutions involve an exhaustive search that leads to exponential execution time, in the worst case, as problem size increases. This problem is called combinatorial explosion. Thus, much of the research effort is devoted towards reducing the search time through developing proper models, and good branching heuristics. A proper model is one that precisely describes a problem using simple and concise constraints, which can be handled by means of efficient and low-complexity algorithms. It is shown in (Smith, 2006) that the model used in problem solving could have a significant effect on solver speed in finding solutions or proving that no solutions exist.

Simultaneously, branching heuristics specify the order in which variables and values are chosen for assignment. As branching heuristics guide the solver towards areas of interest in the search space, their choice could be crucial in effectively solving the problem. Many variable ordering heuristics have been proposed and evaluated in the literature, where some heuristics are based on the domain size, while others are based on the structure of the CP problem. For instance, a heuristic called MinDom selects the variable with the minimum domain size first. This heuristic is based on the principle that gets the most difficult decision done first. Another heuristic called MostConstrained, based on the same principle, prefers variables which are most constrained (i.e. participating in many constraints) (Gent, et al., 1999). In this paper, we will show the effect of using different variable ordering heuristics to solve our maintenance scheduling problem. The state of the art on value ordering heuristics can be found in (Van Beek, 2006).

2.3 *Multi-objective optimisation*

Many real world optimisation problems naturally include multiple objectives (Lesaint, et al., 1998) (Gomes, et al., 2007) that could be handled in many ways (Marler & Arora, 2004). The most common technique is weighted objectives, which aggregates objective functions into a single function through linear weighted summation. Scalar weights of objectives are specified according to their relative importance.

3 THE CP MODEL

In our maintenance scheduling tool, we assume that each task has an expected duration, execution time windows (e.g., Monday 9:00 am–12:00 pm), and a set of maintenance engineers. Additional information such as impact on energy consumption is also provided. Furthermore, our maintenance scheduling problem considers multi-objective optimisation using the weighted objectives technique.

3.1 *Variables*

The set of tasks to be assigned starting times and the set of engineers to be allocated the scheduled tasks are denoted by T and R, respectively. Each task $i \in T$ has a set of variables representing task start time t_i, the assigned engineer c_i, the total cost x_i of scheduling the task at the specific starting time, and an auxiliary variable s_i that links start times to an array of costs. Additionally, an auxiliary variable tc_i is defined to represent both the assigned starting time and the selected engineer in one unique value. The domain of variable tc_i contains combined values of the set of possible starting times and proposed engineers. Finally, the total cost of the schedule is represented by variable p, where the boundaries of the domain of this variable contain the minimum and maximum costs of the schedule.

3.2 *Constraints*

The model contains constraints of the following type, depending on the problem:

$$\textit{concurrent}: t_i = t_j \qquad (1)$$

$$\textit{precedence}: t_i + d_i \leq t_j \qquad (2)$$

$$\textit{non overlap}: (t_i + d_i \leq t_j) \vee (t_j + d_j \leq t_i) \qquad (3)$$

These constraint types define inter-dependency relations that might occur between tasks including concurrency, precedence, and non-overlapping, where d_i represents task i expected duration. In our scheduling problem, tasks have fixed durations regardless of the allocated engineer.

Additionally, for each task i or task pair t_i and t_j, the following constraints are defined:

$$tc_i = c_i * C + t_i \qquad (4)$$

$$t_i = tc_i \% C \quad (5)$$

$$c_i = c_j \Rightarrow (t_i + d_i \leq t_j) \vee (t_j + d_j \leq t_i) \quad (6)$$

$$p = \sum_{i \in T} x_i \quad (7)$$

$$element\ (s_i, dt_i, t_i) \quad (8)$$

$$element\ (s_i, t\cos t_i, x_i) \quad (9)$$

Constraints (4) and (5) link values of variables c_i and t_i with tc_i. Thus, each set of unique values in the domains of these variables corresponds to a unique value in the domain of tc_i. C is a constant representing the total number of slots per week. Variables tc_i are used during search to simultaneously assign a start time and an engineer for each task and they experimentally give better performance compared to carrying out the assignment of start times and engineers in separate steps.

Constraint (6) defines the disjunctive constraint. In scheduling, a global constraint labeled Disjunctive is usually used to model unary resources, i.e., with unit capacity. However, this constraint assumes that the allocation of resources to tasks is done a priori, while our scheduling problem allocates resources to activities during problem solving. Consequently, the disjunctive global constraint is not suitable in the context of our scheduling problem. Inspired by the efficient and simple constraint model proposed in (Grimes, et al., 2009) to solve open shop and job shop scheduling problems, we use the simple representation depicted in (6) for disjunctive constraints.

Constraint (7) states that the total cost of a solution should be equal to the sum of the total costs of individual tasks. Finally, constraints (8) and (9) associate start times with costs, where dt_i and $t\cos t_i$ are arrays containing task i possible start times and costs, respectively. The use of these arrays allows us to represent irregularities in available time slots and non-linearity in costs. The *element* (I,S,X) constraint states that X should be equal to the *Ith* element in the list S (i.e. $S[I] = X$).

4 BRANCHING HEURISTICS

This section presents the two branching heuristics whose application to our maintenance scheduling problem lead to the best results. First we describe the Dom/Wdeg heuristic which performed best among the existing branching heuristics. Then we introduce our newly developed heuristic ModReg.

4.1 *Dom/Wdeg heuristic*

Some of the variable ordering heuristics use information gathered during constraint propagation to produce effective variable ordering. Among these heuristics is the Dom/Wdeg, which is based on a weighted degree that enhances variable selection through incorporating failure based knowledge (Boussemart, 2004). In this heuristic, each constraint is initially assigned a weight of one that is increased whenever constraint propagation results in a domain wipe-out, i.e., a variable domain becomes empty. The weighted degree of a variable is the sum of the weights of the constraints associated with that variable. Dom/Wdeg selects the variable that minimizes the ratio of the domain size to the weighted degree.

4.2 *Modified regret heuristic*

Our newly developed heuristic is based on regret. The regret of a variable x_i is defined as the additional cost (regret) to be paid over the cost lower bound if x_i is not assigned the value at the lower bound. Thus, the regret heuristic suggests assigning first the variable with the highest additional cost so as to minimize the risk of increasing the solution cost if the best assignment becomes infeasible due to wrong heuristic decisions (Milano, 2003). Regret in our scheduling problem is the difference in cost between the earliest and second earliest start times. Additionally, we extend the regret heuristic by breaking ties through selecting the task with the minimum number of starting time slots with zero cost (as delaying the assignment of this task could result into increasing the total cost) or with minimum duration.

5 EXPERIMENTAL EVALUATION

In our experiments, we implemented two constraint models that use different search routines to assign the *tc* variables. The variable ordering heuristic adopted in the first model is Dom/Wdeg, while the second model uses ModReg. In both models, the domains of the *tc* variables are enumerated such that the value representing the engineer with the earliest starting time is selected first. We developed these models using Choco, a java constraint solver (Laburthe & Jussien, 2010).

We built a test case generator that randomly generates test cases with different problem sizes and constraint relations. In this context, problem size refers to the number of tasks in each test case. Generally, we use uniform and inverse cumulative distributions in the random generation of different specifications of tasks. In particular, we use uniform distributions to generate for each task the number and identifiers of possible engineers and the response time window. Additionally, uniform distribution is used to generate the number of tasks in a relation.

In our test case generator we assume the following: up to 4 possible engineers could be generated for any task and the maximum number of tasks that could participate in a dependency relation is 4. Additionally, the total number of maintenance engineers is 15. The response time window for a task could either be 4 hours for emergency maintenance, 1, 2, 3, 7, or 15 days for non-emergency reactive maintenance, or up to one month for planned maintenance. Emergency maintenance is a special case of reactive maintenance that causes threat to health and safety and is usually related to a gas, electricity, or water problem (e.g. gas leak).

Table 1 shows features that have probability distributions in the test case generator, including dependency, duration, maintenance type, missed window, and energy consumption. In the following, we will provide description for each feature. The dependency feature refers to the probability distribution of dependent (i.e. participating in any dependency relation) and independent tasks, while duration indicates distributions of different durations ranging from 1 to 4 slots. Slot granularity is assumed to be 30 minutes. Additionally, maintenance type points to the distributions of planned, reactive, and emergency maintenance.

Energy consumption provides distributions of maintenance tasks related to energy consuming faulty components (i.e. consuming energy excessively during malfunctioning). In case a task specification considers energy consumption, then either low, medium, or high energy levels are generated with distributions shown in the table. Additionally, we take into consideration that the levels of excess energy consumed might differ from day to night hours, e.g., heating systems in offices.

Missed window refers to the time window already passed from task response time before its scheduling. If a task specification will include a missed time window, then the window size is generated randomly using uniform distributions. For non-emergency reactive maintenance, the missed time window could include up to 15 days, while for planned maintenance its maximum size is one month.

We test the performance of the presented models using test cases with problem sizes 20, 50, 70, 100, and 120. For each size we generate randomly a set of 10 scenarios. Moreover, in order to avoid extended search time, we set a solving time limit of 10 minutes. Tests were carried out using 2.40 GHz Intel Core 2 Duo PC with 3.48 GB of memory and running Windows XP.

Figure 1 plots average and median times to prove optimality versus problem size for the two models. Time to prove optimality is the time the solver spends to prove that no other solution with better cost exists. This figure shows that our ModReg heuristic results into a significant improvement in performance. In large problem instances, the average time to prove optimality is reduced by approximately 60%. More importantly, the median time is two orders of magnitude less.

The difference between the average time to find the best solution and average time to prove optimality for Dom/Wdeg and ModReg is plotted in Figure 2. This Figure shows that when the problem size is ≤50, there is an insignificant difference between the two heuristics. However, when the problem size increases ModReg significantly reduces the time gap between finding the best solution and proving its optimality.

Table 1. Probability distribution of features in the test case generator.

Feature	Value	Prob. (Feature)
Dependency	0 (dependent)	0.55
	1 (independent)	0.45
Duration (number of slots)	1	0.50
	2	0.30
	3	0.10
	4	0.10
Maintenance type	1 (Planned)	0.50
	2 (Reactive)	0.40
	3 (Emergency)	0.10
Energy consumption	0 (without)	0.45
	1 (energy, low)	0.35
	2 (energy, medium)	0.15
	3 (energy, high)	0.05
Missed window	0 (no missed)	0.80
	1 (with missed)	0.20

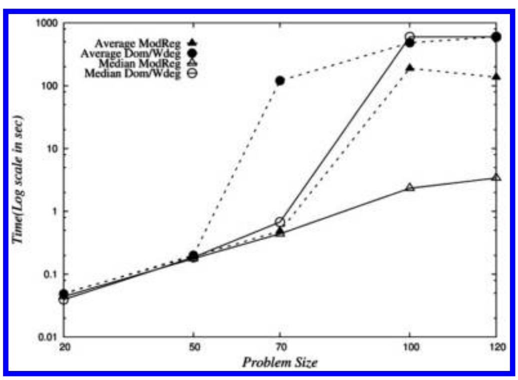

Figure 1. Time to prove optimality using Dom/Wdeg and ModReg.

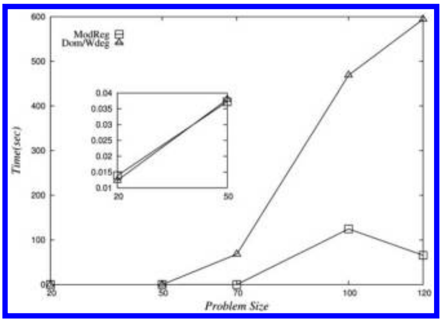

Figure 2. Difference between average time to prove optimality and time of best solution.

Additionally, through cost-based knowledge guidance, the solver is able to prove optimality for 90% of the test cases compared to 62% for Dom/Wdeg. Furthermore, ModReg realizes lower costs for the few test cases in which the solver fails to prove optimality within the predetermined time limit. Generally, our maintenance scheduling tool could provide an optimal schedule for up to 120 tasks in approximately 2.25 minutes on average, and a median time of 4 seconds. This speed demonstrates that the maintenance scheduling tool can be deployed in an interactive environment, allowing a manager to update and improve schedules as new fault and service requests are posted.

6 CONCLUSIONS

This paper introduced a building maintenance scheduling tool that uses constraint programming techniques and cost-based reasoning to generate optimised weekly schedules. These schedules accommodate a wide variety of constraints including time window, resource availability, concurrency, precedence and non-overlapping. Experimentally, we show the computational benefits of using our newly developed heuristic ModReg. This heuristic outperformed the Dom/Wdeg heuristic to optimally solve large problem instances. Generally, our maintenance scheduling tool produces optimal schedules for large problems in a short period of time.

In follow-on work, we are currently investigating the modification and addition of global constraints that exploit problem structure and cover obvious missing deductions, with the aim of speeding up search and optimally solving larger problem instances.

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Methodology for maintenance management utilising performance data

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ABSTRACT: In the life cycle of a building the cost of maintenance greatly outweighs the cost of designing and constructing a structure. Therefore, by providing a method for managing maintenance effectively, the overall cycle costs of a building can be reduced. When you combine this fact with the increase in availability of ICT and reducing cost of sensing and metering devices, it is clear that it is now viable to provide a methodology for carrying out building maintenance through data mining with ICT support. This paper presents a methodology of maintenance management for an existing building. The method will be used for solar system performance analysis. This paper is a proposal to realize this analysis for solar system maintenance management.

1 INTRODUCTION

As more innovative components are introduced into buildings, and as efforts are focused on increasing user comfort and energy efficiency in buildings, the requirement for facilities maintenance increases. As a result of this, optimal maintenance planning and scheduling is of high importance, in order to reduce life cycle costs. Previously, maintenance in commercial and domestic buildings has been quite simplistic but now more focus is being put on analysing building operating conditions in order to predict required maintenance. Moreover, most maintenance activities, where they are carried out, are not usually thorough especially when there is no data on past experience (Sodiya, 2005). Consequently, facility engineers normally follow traditional routines, such as normal checks, repairs and replacements of a few components. In fact sometimes time is wasted through the requirement to check all systems in order to find the faulty component. With decreasing costs of sensing and monitoring devices and increasing cost and complexity of innovative energy provision components, it is now necessary to provide a maintenance management methodology which can detect and process potential failures in components and assign maintenance tasks at appropriate times.

2 MAINTENANCE MANAGEMENT

Maintenance is a major activity in a building's life cycle. It costs many times more to run a building over its lifetime than to build it. The management of building facilities is essential to achieve better reliability and availability of these equipments. Maintenance Management is an orderly and schematic method for planning, organizing, monitoring and evaluating maintenance activities and their costs (RPS for INAC, 2000). Maintenance Management is defined as "All the activities of management that determine the maintenance objectives or priorities (defined as targets assigned and accepted by the management and maintenance department), strategies (defined as a management method in order to achieve maintenance objectives), and responsibilities and implement them by means such as maintenance planning, maintenance control and supervision, and several improving methods including economical aspects in the organization." (EN 13306:2001, 2001). A good maintenance management methodology will enable better equipment performance higher quality of indoor environment, lower operating costs and more effectiveness of maintenance activities.

2.1 *Types of maintenance*

In maintenance a building, there are usually several strategic options available to management and many alternative decisions to be considered (Horner, 1997). In general, maintenance can be classified into four types:

- Routine maintenance—simple, small-scale, ongoing activities (such as cleaning restroom, clearing out gutters and down-pipes, repainting timber doors etc.) associated with regular (daily, weekly, monthly, etc.) and general upkeep of equipments, machines, plant, or system against normal wear and tear.

- Emergency maintenance—urgent activities for sudden and unexpected failure of system or equipment. These breakdowns are unpredictable and irregular so that are more difficult to schedule and plan.
- Corrective maintenance—repair is done when a component has failed or broken down, to bring it back to working order. Activities undertaken to inspect, isolate, and rectify a failure so that the failed equipment or system can be restored to its normal operable situation. It should be the result of a regular inspection which identifies the failure in time for corrective maintenance to be planned and scheduled, then performed during routine or planned plant outage.
- Predictive maintenance (Condition-based maintenance)—evaluate the condition of equipment by performing periodic or continuous equipment condition monitoring. Repair is based on the result of inspections or condition-monitoring activities which are themselves scheduled on calendar time to discover if failure has already commenced. Vibration monitoring and on-stream inspections are typical examples of on-condition tasks (Narayan, 2003).
- Testing or failure-finding—is aimed at finding out whether an item is able to work if required to do so on demand. It is applicable to hidden failure and non-repairable items (Narayan, 2003).
- Preventive maintenance—is a schedule of planned maintenance activities aimed at the reduction of the probability of occurrence of failure and avoidance of sudden failure. It is to prevent the failure of equipment before it actually occurs. It is carried out on the basis of age-in-service and the anticipated time of failure. Thus, if the estimate is pessimistic, it may be done even when the equipment is in perfect operating condition (Narayan, 2003).

2.2 *Information management*

Traditionally, most maintenance data are stored as spreadsheets or in ad-hoc databases. The traditional method for managing maintenance activities is to create activities' report from these data, but not to analyse the contents of these reports. Accordingly, it is recommended using intelligent equipment and automatic maintenance scheduler to enhance maintenance quality and efficiency (Tse, 2002).

Operation services focus on ensuring the efficient energy usage and the cost effective operation of buildings by providing the required maintenance services to end users and building owners. With increasing demands for monitoring information also comes a requirement for quality maintenance data and effectiveness methodologies for analysis of component states. The resulting information is helpful for informing decisions. Time is a key factor in any decision-making process. It makes a limitation of gathering and analyzing data (Narayan, 2003). Facility managers have to make decisions even when the information is incomplete or not entirely accurate. With incomplete or incorrect information, they probably will make poor decisions. Therefore, data quality and timeliness are always at a premium (Narayan, 2003).

Data can be generated internally and externally, and may be formal or informal (Chanter, 2007). Resources of data are history reports, activities' worksheets, free text, sensors etc. with non format or code format. Data collection is quite significant process of management and analysis. All quality data have to be codified to fixed format. Then all maintenance data are stored in data warehouse to support analysis for right decision-making. Figure 1 shows maintenance management and analysis diagram.

2.3 *Failure detection*

There are a number of different types of failure which can occur, they are follows:

- Critical and degraded failures—as a result of failure the system may be totally incapacitated such that there is a complete loss of function.
- Evident failures—when the impeller of a pump wears out, the operators can see the change in flow or pressure and hence knows about the deterioration in its performance.
- Hidden failures—by contrast, are unknown to the operators during normal operation. Once equipment complexity increases, the designer

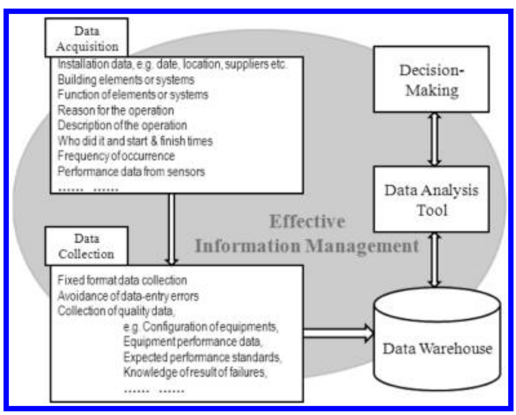

Figure 1. Maintenance management and analysis.

provides various protective devices to warn the operator, using alarms or bring it to a safe condition, using trips. These protective devices are rarely called upon to work and so they are subject to hidden failures.
- Incipient failures—if the deterioration process is gradual and takes place over a period of time there is a point where we can just notice the start of deterioration.

In order to perform maintenance activities, the cause of failure is required. There are a number of methods such as Fault tree analysis and Root cause analysis. Fault tree analysis is a graphical representation of the relationship between the causes of failure and the system failure mode. Designers use it to evaluate the risks in safety systems. It can also be used in facility management failure prediction. Root cause analysis is used to improve reliability by identifying and eliminating the true reasons for a failure. There is a number of quality tools used in carrying out root cause analysis, such as the Kepnor—Tregoe methodology, the change model and differentiation technique, the fishbone or Ishikawa analysis technique.

3 CASE STUDY

In order to evaluate the proposed methodology for a hybrid HVAC system, a case study is carried out on the Environmental Research Institute, (ERI). This building is part of University College Cork and is located on the Lee Road, Cork. It is a multi-use building incorporating labs, open plan offices, conference rooms and a clean room.

The building implements a natural ventilation strategy. It has been designed with a passive solar architecture and improved insulation levels. There are a number of Air Handling Units present in order to ventilate the clean rooms and toilet areas. These units are fitted with heat recovery units. Underground aquifers, located near the ERI, provide water to a Heat Pump system, which in turns feeds an under floor heating system.

Figure 2. Environmental research institute.

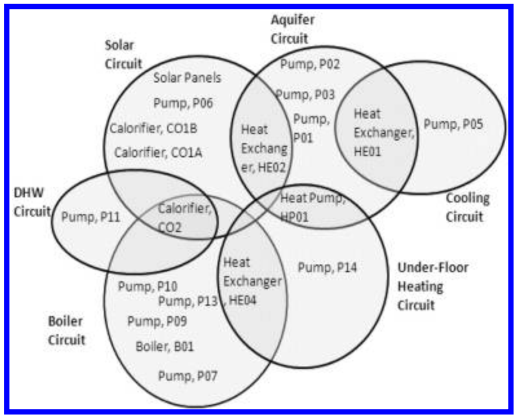

Figure 3. ERI HVAC system interactions.

There are also solar panels located on the roof of the ERI. The main purpose of these panels is to provide domestic hot water, but under certain control strategies they are utilized to preheat water from the underground aquifers prior to entering the Heat pump. There are two types are solar panels present, flat plate collectors and vacuum tube collectors. Four out of six of these circuits consist of 6 flat plate collectors connected in series. Another circuit consists of 4 flat plate collectors connected in series and finally, one circuit consists of 2 solar vacuum tube collectors connected in series.

All systems in the building are monitored by a Building Management System (BMS). There are 280 wired sensors, meters and actuators present and 108 wireless sensors present.

There are interactions between all the hybrid HVAC systems in the ERI, see Figure 3. This leads to inter-system dependencies and requires more complex management of maintenance activities.

The following section will describe the methodology to be used in order to management maintenance activities for the hybrid HVAC system.

4 METHODOLOGY FOR MAINTENANCE

In order to facilitate maintenance of components where the failure of a component is avoided and also whereby only necessary maintenance activities are carried out, we propose using a methodology called performance based maintenance, (Menzel & Tobin, 2009). Performance based maintenance is a meeting point between reactive and planned maintenance. Unlike reactive maintenance, a cost can be assigned to performance based maintenance activities during budgeting and unlike planned maintenance, no unnecessary maintenance activities are carried out.

For performance based maintenance (PBM) to be utilized, performance data from components and detailed knowledge of the design and operational management of the systems are required. The following paragraphs outline the methodology for prepare this information in a suitable format for PBM to be carried out. For this description, the methodology will take examples from a hybrid HVAC system in the ERI building.

4.1 *Classification of components*

The first step is to provide a classification of components which are present and to provide a classification of maintenance activities to be carried out. Using ASHRAE and CIBSE guidelines, a classification system for HVAC components was provided, (Menzel & Tobin, 2009).

4.2 *Tracking failures within systems*

When a component fails, there can be a number of possible reasons. It is necessary to document these reasons or causes before PBM can be initiated, Table 1.

As well as all possible causes of a failure, the relationship between a failure in one component and another needs to be traced, (Stack & Tobin, 2010). This is performed using UML state chart diagrams, Figure 5. When a number of systems are present it is necessary to trace the effect of failures in one system on another system.

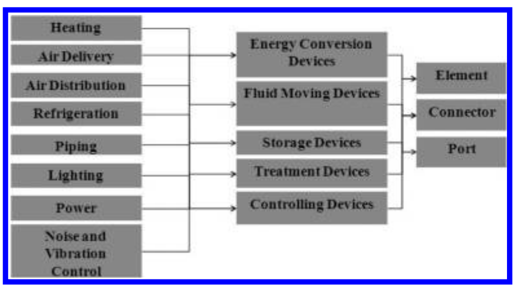

Figure 4. Building service component classification.

Table 1. All possible causes of failure for solar panel (Vitosol).

Fault	Cause of fault
Loss of system pressure	Loss of nitrogen in diaphragm Expansion vessel
	Loss of heat transfer medium
Flow rate discrepancy	Air in system
Loss of power	Electrical cables not tight enough
	Damaged cables

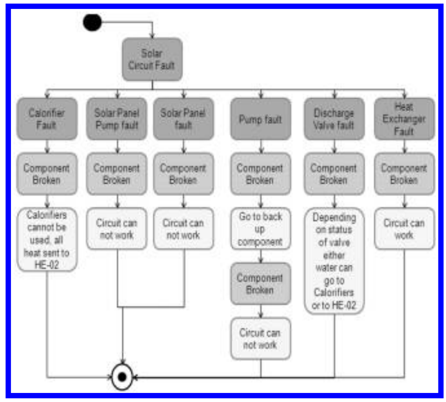

Figure 5. State chart diagram for failure interactions.

These Diagrams determine the priority of the failure which has occurred, by specifying whether the failure will lead to an overall failure of the system or perhaps just to a reduction in the performance of the system.

The following steps in the methodology address fault detection within these systems, by analysing how to identify when performance of a component is actually reducing. This will be achieved through utilising performance data gathered by the BMS.

4.3 *Sequencing of systems*

The operation of components and systems will influence the monitoring of their performance, therefore it is necessary to document the sequence of operation of all components to be maintained using PBM. This involves specifying the order, in which components are activated, the relationships between the activation of one component and another, i.e. when component A is required, then component B is activated and then valve C is opened and only then can component A be activated.

4.4 *Identification of performance measurement positions*

The parameters of each component or system, for which monitoring is required, need to be specified. When these parameters, such as temperature or pressure drop, are included for monitoring, a sensor is position on the component. The location of said sensor must be documented clearly to be able to validate appropriately the readings obtained.

For example, in Figure 6, by analysing the temperature in and out of the Heat pump, A2 and A3, its performance can be determined.

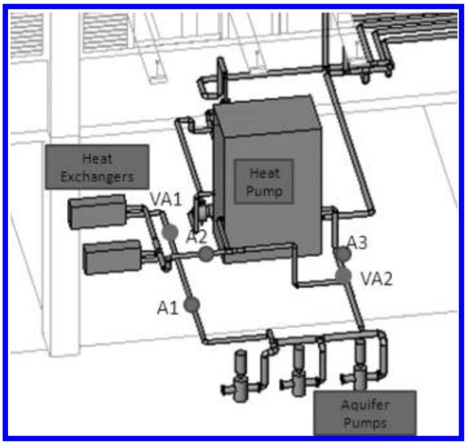

Figure 6. Performance measurement for Heat pump system.

4.5 *Formulation of rules for component performance*

Finally, rules are required to discover if the performance of a component or system is reducing. For each component, there will be unique formulae which will best predict the performance and these formulas will utilize the data for the sensors which are recording the specifying parameters of the component.

To be able to predict when PBM is required, the performance data has to be mined, using data mining techniques, against all factors which influence the performance, then it can predict where maintenance is required or not. The next section will describe how to implement this methodology for a component n the hybrid HVAC system. For this paper, the actual data mining for the performance criteria of the components will not be carried out. An outline of the methodology for the process will only be described.

5 USE CASE SCENARIO

5.1 *Introduction*

For this paper, a use case scenario for PBM is illustrated using a component from a hybrid HVAC system. The specific components are flat plate solar panels. The purpose of these solar panels is to provide domestic hot water to the ERI building. They are located on the roof of the building, and are positioned at an angle of 45°.

5.2 *Solar technology*

Solar thermal systems use energy from the sun to heat water. They are most commonly used for domestic hot water needs. The systems use a heat collector in which a fluid is heated by the sun, (Oughton & Hodkinson, 2008). These collectors are usually positioned either on a south façade or on a roof top.

There are four main types of collectors, swimming pool absorbers, flat plate collectors, concentrating collectors and vacuum tube collectors. A flat-plate collector consists of a shallow metal or wooden box which has a glass or plastic transparent cover, and which contains a black absorption plate that transfers heat to some fluid. The sun's shortwave radiation passes through transparent cover, enters the collector and heats a fluid, (Capehart & Turner & Kennedy, 2008).

For this use case scenario, we will focus on flat plate collectors. There are a number of required components for these solar panels to provide domestic hot water, see Table 2, (Eicker, 2003).

Table 2. Components for domestic hot water solar system.

Components	Dimensions
Vacuum tube collector	1.25–1.5 m^2 person
Storage tank (pressurised)	40–70 l per m^2 collector area
Heat exchanger	30–40 W/K power per m^2
Pipe-work	–
Pump, exp. vessel, valve	25–80 W pumping power
Controller	Relay for pump control

Each of these components will have particular rules to determine their performance. Each component can be assessed with regard to the flow rates and temperatures in and out and power consumed. For this research paper, a focus will be placed on the solar panel itself, as its performance is influenced by exterior conditions. Therefore, in order to determine if its performance is acceptable, the weather conditions need to be analysed at the same time.

5.3 *Solar panel performance*

The method for evaluating the performance of these solar panels is to use the following equation which is provided by Vitosol in the user manual:

$$\pi = \pi_\circ - \frac{k_1 \Delta T}{E_g} - \frac{k_2 \Delta T^2}{E_g} \quad (1)$$

where:
π = efficiency,
$\pi_\circ$ = optical efficiency,
k_1 = heat loss coefficient 1,
k_2 = heat loss coefficient 2,
ΔT = difference in temperature between fluid inside and ambient temperature outside,
E_g = specific thermal heat capacity.

Table 3. Flat plate collector values.

Variable	Value	Units
$\pi_\circ$	84	%
k_1	3.36	$W/(m^2 K)$
k_2	0.013	$W/(m^2 K^2)$

A number of the values are specified by the manufacturer, as can be seen in Table 3.

The manufacturers specify the efficiency as between 0.5–0.68. This provides a range for determining if the collectors are operating at the expected range.

ΔT is the difference between the absorber surface and the ambient outside temperature. The absorber surface is complicated to measure. It is" a function of the distance from the heat removing fluid tubes and the flow length. An average value can only be determined from a measured temperature distribution". Instead, the mean fluid temperature between the inlet and outlet can be used, as long as the flow rate is not too low. Therefore:

$$\frac{T\text{Fin} + T\text{Fout}}{2} - T_{\text{outside}} = \Delta T \quad (2)$$

From the BMS system present in the ERI building, the values for T_{Fin}, T_{Fout} and T_{outside} can be determined.

The proposal of this paper is to apply equation 1 to historical and real time data being stored in a data warehouse as part of a project entitled ITOBO. By applying the equation, the performance of the solar panels can be determined. This value is then checked against the expected values provided by the manufacturer as stated above and against other influences, such as the number of sunshine hours, total irradiance. It can then be determined that if the performance is below the expected range for the particular wind conditions, then maintenance is required by the solar panel.

6 CONCLUSION

With the complexity of HVAC components increasing and the cost of energy rising, maintenance activities have become a crucial part of the life cycle costs of a building. In this paper, a literature review has presented the current state of building maintenance management. A methodology has also been presented as an alternative to the current methods of scheduling maintenance activities.

This methodology requires (1) for components to be monitored at defined parameters, (2) for sequence of operations of systems to be mapped, (3) for all possible faults to be identified, (4) interaction of faults within systems, including dependencies, (5) priority of these failures to be corrected, and finally, (6) for rules to be created to monitor the performance state of each component.

7 FUTURE WORK

Data mining is required in order to complete this methodology. By taking the performance rule and stating the parameters which influence the performance, one can create a model which will predict when the performance of the component will reach a prescribed value, and so can predict when maintenance will be required.

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Information technology for energy-efficiency

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IntUBE energy information integration platform

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ABSTRACT: Buildings are one of the major contributors to energy use and CO_2 emissions. The energy used in buildings accounts for about 40% of the total energy use in Europe. The main aim of the IntUBE project (http://www.intube.eu) is to develop intelligent Information and Communications Technologies (ICT) to improve the energy efficiency of these buildings. IntUBE will primarily focus on integrating existing software functionalities using open standards and their open source implementations. Based on the open data from multiple life-cycle stages (especially 'design' & 'operate') new advanced services will be developed to inform inhabitants in intelligent ways of how to change their energy consuming behaviour in ways that reduce energy consumption and improve comfort. This paper will show how W3C Semantic Web technologies [1] like Resource Description Framework (RDF), Web Ontology Language (OWL) and SPARQL semantic query language can be used to its fullest to model the buildings, their installations, usage and performance; 'as-planned' in the design stage and 'as-built' in the operational stage.

1 INTRODUCTION

The overall IntUBE (software) system is to process energy data acquired from buildings and neighbourhoods, with which operational processes are to be performed in order to obtain qualitative data which can be used by different stakeholders (inhabitants, owners, technical managers, decision makers, energy providers, and design team) to improve buildings energy efficiency and reduce their energy consumption in the operational stage.

The integration platform will store and provide all information coming from the design and simulation applications and the Building/Neighbourhood Management System (BMS/NMS) which can for the moment be considered as its main clients. The platform will ensure fluency and coherence between all the IntUBE software components.

2 PLATFORM ARCHITECTURE

At the platform level, there are two separate sides as shown on figure below:

- One side for the clients,
- Another side for the servers.

The services provided by the platform support the interaction of the processes and methods required by clients. It is necessary to implement a client proxy to communicate with the servers. At this level, the user talks with the servers through a web client, that is to say a program capable of communicating with web servers, requesting and receiving information from them, and processing it for display or other uses.

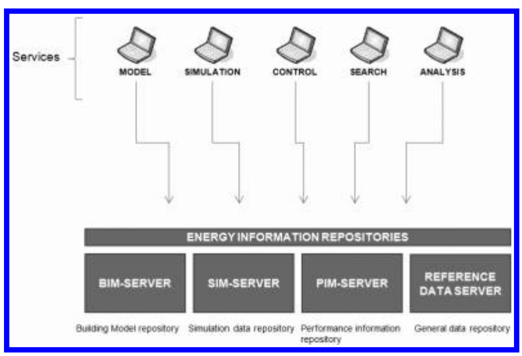

Figure 1. Client and server sides.

There are four different types of servers that can be instantiated multiple times, with an energy information repository to link them together:

- The goal of a *Building Information Model (BIM) Server* is to store the building models. There are two major categories of models: pre-design models (e.g. a schematic, simplified definition of the building) and complete models (e.g. a detailed description of the building).
- *Simulation Information Model (SIM) Servers* store the data generated by simulation programs, that is to say, the input data provided by the user and the output data generated by the simulation application.
- The *Performance Information Model (PIM) Server* is responsible for storing real data from building monitoring (and simulated data, in the context of the *alternate option*), as well as the status of the HVAC equipment.
- A *Reference Data (RD) Server* stores the metadata of the whole data stored in the other servers to speed up queries. It is also responsible for grouping the data (models, simulations, and monitoring data) of each building and assigning Globally Unique IDs (GUIDs).

3 ENERGY MODEL

One of the key components of the IntUBE Energy Information Integration Platform is the "IntUBE Energy Model", the set of information structures used by the different servers defined earlier: BIM server, SIM server and PIM server. The RD server is conceptually treated but not taken into account in here.

Following a typical three-level protocol stack as depicted in Figure 2, we distinguish a common semantic data structure where all relevant CAD and energy-related software applications (for design, energy profiling, building automation etc.) exchange and/or share their common data. The syntax/format for both this information structure and the actual valid information instantiations will be defined using open standards. This will make it possible for software applications to import and export information valid against the data structure.

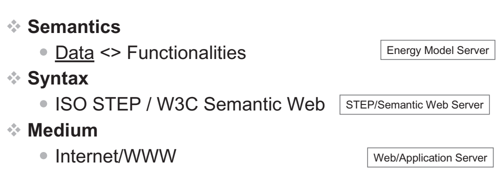

Figure 2. Three abstraction levels for the energy model.

Furthermore, access methods will be defined again in an open standards way to directly access the common information (abstracting from the actual data format decided). Finally the medium is decided over which the common data will be transferred (typically the Internet/WWW).

This three-level approach at the same time depicts a three-level server situation: on the lowest level we expect a web server or an (web) application server. Choosing certain technologies for syntax results in for instance a STEP [2] server (speaking EXPRESS and SPFF languages) or in our case a Semantic Web server speaking RDF and supporting access mechanism like SPARQL queries. Finally, choosing/defining a specific data structure (n the form of a schema or ontology) one can provide a specific server in our case an Energy Model Server.

The "IntUBE Energy Model" semantics will address a wide variety of relevant planned/actual & static/dynamic building information:

- The Building Information Model (BIM) as-designed
  - Building Context (built environment, weather, etc.)
  - Building Structure (zones, spaces, rooms)
  - Building Elements/Parts & Materials
  - Information on energy installations (heating, cooling, ventilation etc.)
  - Explicit Shapes (typically placements, topology & geometry)
- The usage of the building as planned
- The planned (energy) performance of the building
- The same building but now 'as-built' and its actual usage and performance (potentially provided via a BMS communicating to sensor networks).

4 RELEVANT TECHNOLOGIES

In IntUBE deliverable D6.1 we described the 'state-of-the-art' with respect to available standards and technologies for approaching energy information integration. We identified the following four main streams:

- BuildingSmart/IAI IFC/IFD [3, 4] using ISO STEP technology
- Green Building XML (gbXML) [5] using plain XML technology
- Product Modelling Ontology (PMO) of SWOP [6] using W3C Semantic Web (SW) technology, and
- OGC CityGML [7] using plain XML technology.

To make a decision for IntUBE we considered the following 'design principles' for a Future-Proof

(Energy Information) Integration Platform and its Energy Model as main component:

- Free/Open
  - Independence from any platform, vendor or user group
  - Open Data (structure & content)
  - Open Technology, including Open Source (reference) implementations
- Semantic
  - Smart, model-driven, object-based, 'database-over-drawings'
- Web-based
  - Configurable base communication infra-structure for easy access of all stake-holders through thin clients ('web browser-based')
- International, No 'country-specific' solutions
- Generic, No 'construction-only' solutions
- Flexible
  - Agree Technology, be flexible on actual data structures & content
  - Embed/support legacy technologies
- Support, by existing client and/or server soft-ware applications.

5 SEMANTIC WEB TECHNOLOGY

5.1 *Introduction*

Based on the findings as documented in chapter 4 we decided to go for the most future-proof and flexible approach available: The Semantic Web with (XML-based) standards like RDF, RDFS, OWL (version 2) and the SPARQL query language. This way we are not limited in any way by existing data structures nor outdated underlying technologies. Another advantage is that existing knowledge and tools from the earlier European SWOP project can be readily adapted and reused. A good example is the Product Modelling Ontology (PMO) ("pmo.owl").

Another strong point is the foreseen free/open source implementation potential which supports the building of critical mass of the IntUBE results.

In the next paragraphs we will show how we will apply the chosen technology in IntUBE.

5.2 *SWOP PMO Excel workbook and PMO/OWL2 generation*

When defining our IntUBE information needs we start with a structured Microsoft Excel work-book. For IntUBE we defined an extended and more OWL-based variant based on the one used in SWOP. A sheet template for defining classes is depicted in Figure 3 (one sheet per class, a separate special sheet template is available for user-defined data types).

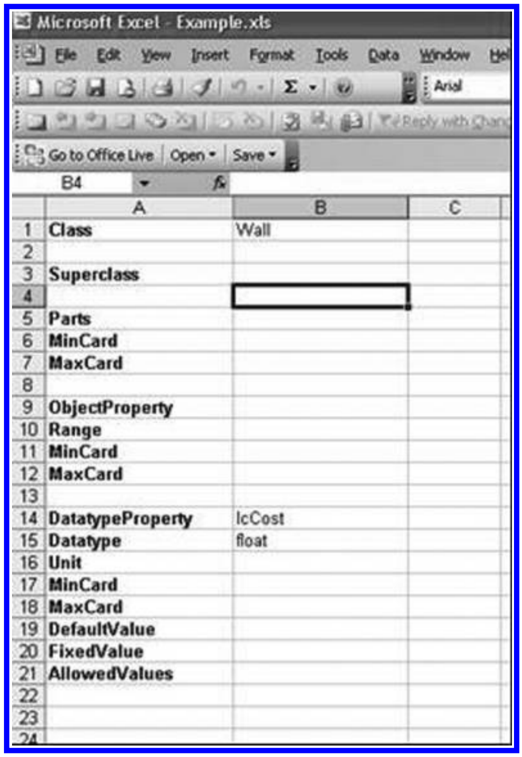

Figure 3. IntUBE Excel sheet template for classes.

This sheet is easy enough to fill in by non-'ontology experts' and still defines all the basic information structures needed for further elaboration. For each class, one defines in a separate tab its relevant (parent) super class, its part classes, its properties ('data type properties'), its relation-ships ('object properties') and relevant details like default values, fixed values, units and underlying data types (basic or user-defined like those involving enumerations). This way one can describe in a (globally) complete way, typically as a 'work-book' involving multiple sheet-tabs, the input and/or output needs for any software application to integrate or any intermediate/neutral information structure agreed. A good example here would be the "IntUBE-EnergyBIM.xls" containing all the agreed BIM data structures.

Next we adapted a SWOP tool called the 'Excel2PMO-Converter' that takes such a work-book and generates the equivalent formal representation in PMO/OWL2 (Web Ontology Language, the prime component of the Semantic Web technology). Hereby we make use of the earlier mentioned Product Modelling Ontology (PMO) developed in SWOP, a reusable upper product ontology providing modelling mechanisms that are

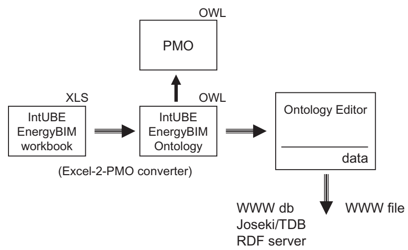

Figure 4. Information modelling approach.

not directly available in the OWL2 language like product decomposition, units and default or fixed values. An example output would be the "IntUBE-EnergyBIM.owl" ontology.

The resulting ontology can be read and if needed enriched by ontology editors like the commercial TopBraid Composer (TBC) or the open source Stanford/Manchester Protégé toolkit. A next follow up is the generation of a database structure (Joseki/TDB [8]).

The complete process is graphically shown in the Figure 4.

We will apply this approach to our IntUBE-EnergyBIM, IntUBE-EnergySIM and IntUBE-EnergyPIM. Once we have our semantic data in the open source HP Joseki RDF-server as Triple DataBase (TDB) we can query and update it via a SPARQL resp. SPARQL-Update interface (at http://joseki.bimserver.org/sparql.html resp. http://joseki.bimserver.org/update.html). The BIM, SIM and PIM ontologies will be kept as separate OWL files on the WWW; only the data according to them will be put in the TDB.

5.3 *Client software integration*

In general there are two ways software application can interact with the integration platform:

- Directly via some API or Query,
- Indirectly via some total file input or output (after many native changes) using some download/upload request or general/unconstrained query.

Since most software applications in IntUBE have their own native storage (files or database) (or are even from third parties) we will concentrate on the second approach.

Typically we want:

- To get data from the platform and use it as input,
- Put data to the platform from our output, or
- Both.

For each link we have to transform our data involving:

- Change of syntax (to/from RDF/OWL) or "translate", and
- Change of semantics (to/from some IntUBE-Energy ontology) or "convert".

One can develop some "transformer" for each link that does it all but one can also/better separate the concerns cleanly and develop a separate translator for the syntax transformation and converter for the semantic transformation. The first one can often reuse existing import/export mechanisms, the latter can be done very nicely by defining a native input or output ontology where data is translated according to the own/native ontology and then converted according to a mapping to the target ontology. If this mapping is specified as a SPARQL (Construct) query you can use any SPARQL engine as generic converter.

6 EXAMPLE: REVIT INTEGRATION

6.1 *Introduction*

The 3D CAD design application Autodesk Revit Architecture 2010 can export Green Building XML (gbXML) data; that is an XML-file according to the gbXML XSD. Our used TopBraid Composer tool can import any XML-file (as "Semantic XML") and generate on the fly an ontology for its structure call it gbOWL in this case. Clearly such ontology is non-validating but can be very handy be used as a source ontology when mapping to the target IntUBE EnergyBIM ontology. We did this on a part of the total Barcelona Pilot building.

When we export this data (without shading faces as option) to gbXML we get a 700 KB XML file that can be imported in TopBraid Composer as a 16 MB OWL file showing for instance 33 Space instances.

This data can now be exported as a TDB database, published by Joseki and acted upon by SPARQL (as in the case where we select data and construct IntUBE-EnergyBIM data.

6.2 *Easier semantic data instantiation*

In the previous examples we used TopBraid Composer to instantiate example content or we get data via CAD sources that are mapped to our ontologies. For IntUBE we adapted an existing SWOP software tool, the PMO Configurator, to make instantiation easier.

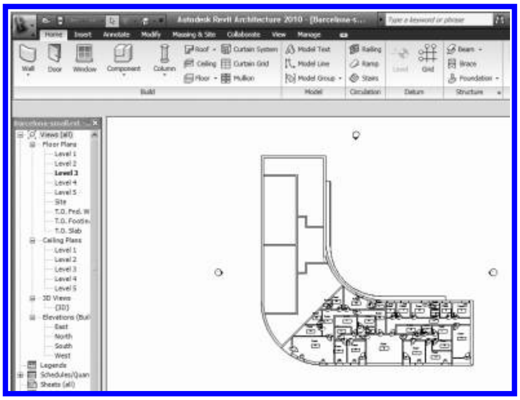

Figure 5. Demo data in revit.

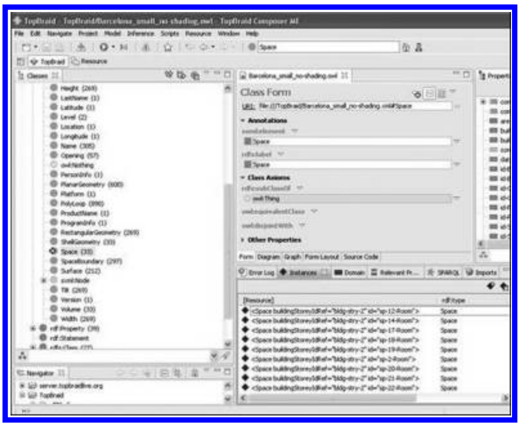

Figure 6. Demo data in TopBraid composer.

This tool can read any PMO-based ontology (like the IntUBE BIM, SIM or PIM ontology or any application-specific ontology that will be mapped to them) and shows to total decomposition hierarchy relevant. An example for IrMonitoringOutput.owl is shown in Figure 7.

Each part or data type property (here: of a MonitoredRoom) can then be instantiated and at any point in time saved to an ontology instance (which could on its turn be read in and enriched for say object property data, by TopBraid Composer and finally be exported and published as Joseki/TDB database.

At this point in time all base OWL constructs including object properties are taken into account. Wished future features are: user-defined instance ID's (now uniquely generated) and data entry-control based on constraints (like allowed enumeration values).

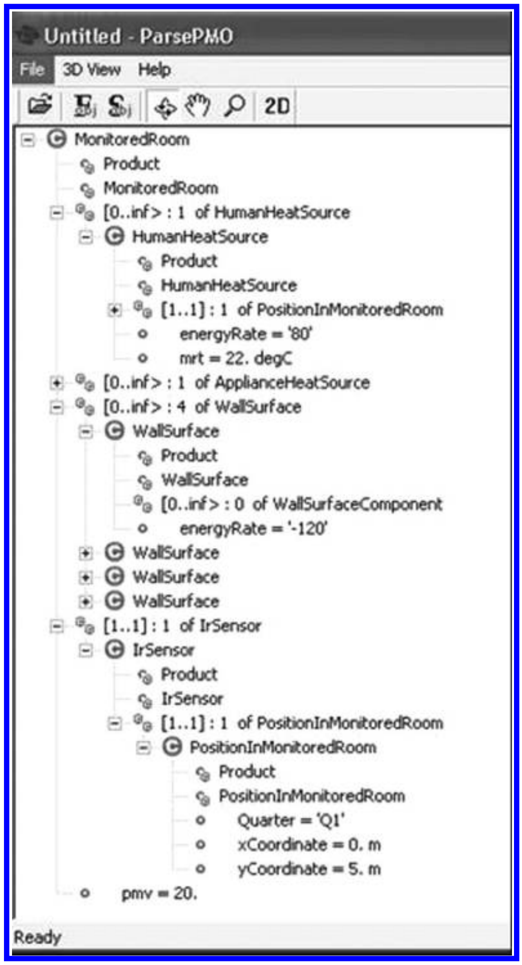

Figure 7. Extended PMO configurator.

7 CONCLUSIONS

7.1 *Architecture*

The platform architecture distinguishes four types of servers/repositories:

1. A Building Information Model (BIM) server: planned static, structural building data.
2. A Simulation Information Model (SIM) server: planned dynamic, behaviour (building usage) data and estimated performance results.
3. A Performance Information Model (PIM) server: actual static ('as-built') and actual dynamic behaviour (building usage) and actual results data.
4. A Reference Data (RD) server: meta-data interrelating the previous three internally, and

externally: relating reference data sets like performance data for several archetypes of buildings.

This 'distinction in four' seems a very useful one separating clearly the concerns and issues.

7.2 *Modelling approach*

We identified three main approaches for protocols used for the BIM aspects: IFC, gbXML & CityGML. They all have their pros and cons (looking at various aspects ranging from technicalities to current commercial software application support). We decided not to be limited by any of them by developing our own 'semantic web'-based ontologies using future-proof semantic web technology (reusing existing IFC or gbXML interfaces where possible when integrating specific client software applications).

Beside the needed critical mass in the from of current application support, semantic web technologies like RDF, OWL and SPARQL seem to be the future for both flexible and powerful product modelling in general and any form of Building Information Modelling (BIM/PIM/SIM) in particular.

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ICT enabled business models for innovative energy management

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ABSTRACT: Holistic Energy Service Provision has the potential to provide new business opportunities for Facility Management Companies, Building Managers, Energy Providers, Maintenance Providers and many other stakeholders currently working in the area of building design, construction, building operation, energy management and maintenance. Producing a transparent and understandable method of information communication and use is difficult because of the complexity and number of variables involved in energy information trading.

This paper describes how the concept of ICT Enabled Business Models could be applied in the area of Energy Information Management. A proposal is presented which describes the context, the relevant stakeholders, required novel IT-services and the concept of "Extended Energy Profiles" to allow easy and standardised exchange of Energy Information amongst potential partners. Standardised methods of communicating ICT Enabled Business Models definitions to other stakeholders of required development of software or hardware is also discussed.

1 INTRODUCTION

Integrated energy service provision and the associated data utilisation has the potential to provide new business opportunities and add value. However, aside from the technical challenges to be overcome, organisational, resource and financial systems need to be defined to maximise potential value and provide a repeatable solution. This paper describes a clear and repeatable method of doing same which has been used successfully in a 36 month EU ICT research project.

2 CONTEXT

According to the "World Energy Assessment" delivered by United Nations Development Programme (UNDP 2005) the global average growth rate of energy use of primary energy is about 1,5% per year. If this rate is preserved throughout the coming years, the total energy use will double between 2000 and 2040, and triple by 2060. This growth rate can no longer be supported. Most importantly, we must reduce our dependence on fossil fuels because their availability is limited (supply issues) and their usage leads to CO_2 emissions contributing to global warming (environmental impact). A substantial part of the energy (approx. 40%) is used to operate buildings. Therefore, the challenges for the construction sector are (i) to improve the energy-efficiency of buildings and (ii) to provide solutions which enable the optimal usage of renewable energy sources.

The development of advanced IT-solutions addresses both challenges. The introduction of advanced Building Management Systems will lead to more energy efficient operation of buildings; the application of Neighbourhood Management Systems will support the easy and efficient integration of renewable energy sources into existing energy networks. These IT-solutions will generate more data and information which document User Comfort and the Performance of systems and components and specify User Demands and available Supply Capacity from renewable energy sources. This information is also called 'Energy Information'. Energy Information could be used by Energy Providers, Facility Managers, Energy Experts and other stakeholders to offer so called 'Value Added Services' to Owners and Occupants of buildings.

Therefore, new business models in the energy sector are required to close the gap between the interests of the different stakeholders in the energy sector, to enable the integrated usage of Energy Information, to support the development of 'Value Added Services', and finally to offer these services in new, innovative ways to clients.

3 BUSINESS MODEL FORMALISATION

To provide a formalised and universally understandable method of communicating business models, a predefined system with set characteristics is used.

Osterwalder (Osterwalder, A., Y. Pigneur, et al., 2005) describes business models according to nine

Table 1. Business model building blocks.

Pillar	Business model building block	Description
Product	Value proposition	Gives an overall view of a company's bundle of services and products
Customer interface	Target customer	Describes the segment of customers the company wants to offer value to
	Distribution channel	Describes the various means of the company to get in touch with its customers
	Relationship	Explains the kind of links a company establishes between itself and its different customer segments
Infrastructure management	Core competency	Outlines the competencies and the key resources required to execute the company's business model.
	Value configuration	The key activities necessary to implement the business model and the arrangement of activities and resources.
	Partner network	Describes the key partners, their motivations to participate in the business model, and the network of cooperative agreements with other companies necessary to efficiently offer and commercialise value
Financial aspects	Cost structure	The cost structure resulting from the business model; Sums up the monetary consequences of the means employed in the business model
	Revenue model	The revenue streams generated by the business model (constituting the revenue model), and the way a company makes money through a variety of revenue flows.

(Source: Osterwalder et al., 2005)

characteristics, which are applicable to any type of business model in any area (e.g. in architecture or engineering). These characteristics are referred to as "building blocks" of a business model and are summarised in the following table.

By using these clearly defined building blocks, it is possible to create an easily communicated structure of the most important aspects to describe a product or service, the customer and interface to the customer, the infrastructure management and basic financial aspects.

This method was used to describe the business models formulated in Section 8.

4 STAKEHOLDERS

When describing business ventures, it is important to identify relevant actors, the distribution/communication channel and their relationships. As this project is concerned with Intelligent Use of Building Energy, the most important stakeholder is the user of energy and their relationship with the ESCO or energy supplier. Table 2 below describes this relationship between stakeholder and the distribution channel of energy supply.

5 EXTENDED ENERGY PROFILES

Rather than getting into the finer details of data/categories/metrics, energy profiles allow exchange of well defined sets of information. The energy utilization can be described in terms of demand, supply, operation, performance, maintenance, and purchase. (IntUBE Work Package 2; Business Models 2009).

Therefore we propose to define a "compressed, focused" format for the exchange and delivery of Energy Information during various phases of a building life cycle. Furthermore, we propose to call these compressed "packages" or "containers" of Energy Information "Energy Profiles," since their information is used to outline or to sketch the energy demand, supply, or usage of a building user, a building system, a building, or even a complex of multiple buildings.

Energy Profiles are used to specify or characterise a certain User Comfort, a related energy demand, an energy supply capacity, a required set of Performance Criteria, and—if required—a set of proposed upgrades/improvements. The list below introduces the following (Energy) Profiles:

- *Operation profile*: This profile specifies the configuration parameters for the Operation

Table 2. Stakeholder descriptions.

Stakeholder	Distribution channel	Relationship
Owner residential	Not available	Owner represented by (Facility) manager or self
Owner-occupier residential	Purchases energy from one or multiple providers	One or multiple contracts with fixed or customized tariffs
Owner commercial owner-occupier commercial	Purchases energy from one ormultiple providers can be represented by FM-provider	Usually customized contract for commercial end users
Occupier residential B	Purchases energy from one or multiple providers Contracts services and energy supply to ESCO	Customised contract Long term contract
Occupier commercial B (usually SME)	Purchases energy from one or multiple providers Contracts services and energy supply to ESCO	Customised contract Long term contract

of the Energy System. It should represent the 'optimum' set of parameters. The operation profile is the result of (an ongoing) simulation and negotiation process.

- *Supply profile*: This profile specifies the characteristics of the supply side on NMS-level. It 'offers' Energy Information about available capacities of the NMS and related prices. The "Supply Profile" could be compared to a quotation. It might lead to a business activity—the purchase of some form of energy.
- *Generation profile*: This profile specifies the characteristics of the demand side on NMS-level. It 'requests' Energy from the NMS. The price was agreed based on the "Supply Profile". The "Generation Profile" could be compared to a purchase order. It may trigger an immediate business activity.
- *Demand profile*: This profile specifies the characteristics of the demand side. It characterises the "desired" User Comfort as specified by the End User. The Demand Profile "requests" a certain "service level". The request will trigger business activities, such as simple energy supply or more advanced more holistic configuration and adjustment of services
- *Performance profile*: The Performance Profile specifies the "design" performance of the systems and components. It can be used for comparison with the"Operation Profile". In case of major discrepancies a"Maintenance Profile" might be triggered.
- *Retrofit profile*: The retrofit profile is used to specify proposed retrofits.

To better define these profiles, generic relationships need to be defined. These profiles describe energy conditions within buildings. Metrics to be included are energy consumed, building type and building areas. For example, energy certificates are a generic method of defining energy performance.

6 STANDARDIZED EXCHANGE OF ENERGY INFORMATION

Having defined a business model framework (Section 3), the most relevant stakeholders (Section 4) and sets of standardized "Energy Profiles" (Section 5), the next relevant step was to document how all relevant activities and exchanges information related to each other in the context of intelligent use of building energy and holistic energy service provision.

This process was documented and communicated using *IDEF0* (*Integration Definition for Function Modelling*) functional modelling language. Figure 1 gives a top level overview of the Activities and Exchanged Information process over the entire building life cycle for this project. The information flow using "Energy Profiles" is split into sections from design to profiling to calibration to operation. Further detailed IDEF0 descriptions of each box and their relationships were also defined. This process allowed the information and activities of the project to be described and is an important step to define, before the business model framework descriptions of any business models were documented or disseminated further.

Mapping this process allows participants to determine if any development of software or hardware is required.

7 BUSINESS CASES

Once a detailed technical description of the project activities was clearly and meticulously created,

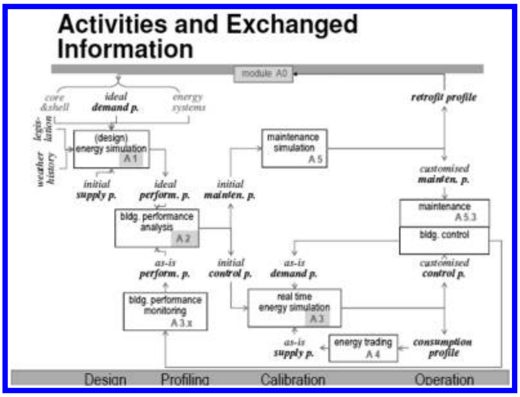

Figure 1. Activities and exchanged information.

the next step was to return to the business model definitions. Before creating business models, it was decided to first create and document some "Business Cases". These cases highlight areas where there is the potential for future business expansion into new business ventures.

These business cases differ from business models in that they provide general descriptions of certain areas of interest without being very specific. For this particular project and for the Activities and Exchanged Information shown in Figure 1, the following business cases were created.

Business case 1: *IT-supported design, installation and operation of wireless sensor networks* to enable efficient and effective installation of sensor and meter modules and central data processing unit.

Business case 2: *Development and implementation of an "Energy BIM"* and associated standardised interfaces for the generation of a specification, documentation, and simulation of Energy Systems (e.g. HVAC, lighting) and related building components (e.g. insulation, blinds, etc.).

Business case 3a: *Development, implementation, and operation of a 'Building Performance Analysis Tool'* for the achievement and storage of sensor data in order to perform short term data monitoring as well as long-term trend analysis relating to optimum operation of the building over it's life cycle. This can be realised using Data Warehouse Technology.

Business case 3b: *Development, implementation, and operation of a graphical user interface front-end* which provides facility management personnel with access to the building operation data and trend analysis as well as allowing the end user to configure the sensor network to monitor and deliver the required data at the required granularity/frequency.

Business case 4: *Development, implementation and operation of a "Real-Time Energy Simulation Service"* and associated standardised interfaces for the generation of calibrated building control profiles supporting demand prediction. This could be realised through the development of advanced Energy Simulation Packages.

Business case 5: *Development, implementation, and operation of a Performance Analyses Tool* which provides facility management personnel with support for trend analysis and detection of malfunctioning systems and components.

Business case 6: *Development, implementation, and operation of a Retrofit Decision Support Tool* which provides facility management personnel and Building Owners with instruments allowing the evaluation of retrofit scenarios and the calculation of an estimated "return of investment".

8 BUSINESS MODELS

Following on from the business cases in Section 7, a number of detailed business models were developed from these in the format described in Section 3. For this particular project, the following eight business models were created and defined. These eight business models are summarized here with an extended description given of Business Model 8 using the defined building blocks from Section 3.

8.1 *BM1: System design, mechanical, electrical and control engineering*

This suggests that there are opportunities for specialist engineering design in the field of local heat trading. This is likely to be in the format of a consulting engineering firm or systems specifier or design & build contractor.

The "core" business activity requires software support in form of modelling and energy simulation packages.

8.2 *BM2: System operational control providing ICT*

This BM suggests an ICT service providing controls for Local Heat trading networks. Whereas BM1 was concerned with mechanical engineering of pumps, pipes, etc, this business model is takes the electronic and controls element into account. This business is likely to be in the format of consultants but there will also be a need for the hardware and controls systems.

8.3 *BM3: Energy centre construction and operation*

BM3 relates to construction and operation of energy centres for local heat trading networks, possibly in the form of independent community operations. Whilst energy centres already exist for large sets of linked buildings (e.g. airports), this BM would concentrate on energy centres for local heat trading networks.

8.4 *BM4: Continuous commissioning and Retrofit activities*

Retrofit and commissioning of existing buildings is going to become far more relevant in the near future than it currently is (Holness, Gordon 2009). There exists the potential for specialist retrofit/commissioning consultants, not just for building & equipment alterations as currently exists, but how to use modern and new ICT systems to exploit the efficiency of existing buildings. This is likely to be related to whole life cycle building simulation.

8.5 *BM5: Subsystems control to maximise energy production depending on market prices*

This business model is entirely ICT and control system related. There are vast complexities related to the most efficient and economic method of energy production and transport when multiple systems are involved. This BM relates to the ongoing and constant determination of which combination of energy sources will be most efficient. Not only will the current energy scenario need to be computed but future demand and storage will also need to be accounted for.

8.6 *BM6: Definition of dynamic energy profiles for trading and real-time use*

As this projects communication concept is based on energy profiles, this business model is seen as a basis activity enabling further energy information related business activities. However, also the definition of tailored and dynamic profiles itself is seen as a service. Therefore, standardised default templates of profiles will be created based on the initial definition of the profiles. Standardised profiles ensure that all devices integrated in the network can communicate among each other.

8.7 *BM7: Building simulation to optimise future energy generation, transmission and usage*

Because future demands and efficiencies need to be taken into account, especially with regards to storage capacity, it is likely that there is a need within the energy service provision sector for using individual building simulation or neighbourhood energy simulation to predict demand, supply and capacities. Consideration also needs to be given to any weather conditions which may affect efficiencies of mechanical plant, e.g. air temperatures on heat loss, solar conditions on renewable generation, etc.

8.8 *BM8: Real time energy simulation for current real-time usage*

This business model suggests that value may be added by providing instantaneous energy information to increase occupant awareness and to support "informed" participation in energy trading, i.e. to make informed decision when and what amount of energy could be consumed depending on flexible energy tariffs.

A full description of this business model is given in the table below.

Table 3. Business model 8 full description.

Pillar	Business model building block	Description
Product	Value proposition	Product offers real time energy simulation information to occupiers to optimize control of buildings in the very near future.
Customer interface	Target customer	Builders owners, occupiers, facilities managers
	Distribution channel	Professional channels. possibly follow on from design or installation of building management systems
	Relationship	Product/Service would be provided as a once off purchase.
Infrastructure management	Core competency	In depth expertise in simulation, building management systems & energy systems
	Value configuration	Could be part of the "Energy service provision package".
	Partner network	Energy producer saves from balanced load, energy consumer rewarded with share of savings.
Financial aspects	Cost structure	Cost of BIM creation and system set up offset by purchase price of product.
	Revenue model	Occupier saves from reduced energy consumption.

9 CONCLUSION

This paper has described a process which has been used to identify potential business opportunities and clearly describe them as business models in a energy information management context. A number of repeatable steps have been described as follows;

1. Creation of business model description framework
2. Description of stakeholders
3. Energy profile description
4. Energy information exchange
5. Business cases
6. Business models.

Whilst the business models in Section 8 are specifically for one particular EU Research project, the methodology used to define the process and identify business shortfalls can be repeated in future projects, both research and commercial.

Following this procedure can allow project participants to extract and define necessary information which may otherwise be lost because of the complexity and number of variables involved in energy information trading and to allow for dissemination and transfer of knowledge.

These specifications and business models are currently under development at University College Cork, Ireland as part of the EU-FP7 project IntUBE (further details at http://zuse.ucc.ie/intube and http://www.intube.eu/). The work presented in this paper is supported by European Union (ICT-2007.6.3 ICT for Environmental Management & Energy Efficiency).

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A functional approach to energy efficiency in museums

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ABSTRACT: Energy Efficiency in Buildings is a process which is strongly linked with Management Systems for AEC environtments. There is no general solution because it depends on the physical domain (indoor and outdoor surrounding space), available equipment and systems, monitoring devices and the "intelligence" of related devices. However, all of them are referred to an Information System, with a vector information as common support for updating and sharing information. Typical functionalities involve to data mining, information processing and analysis, pattern identification for behaviors (involving interaction of humans with the environment), smart diagnosis and adaptive control. Integration of data and functionalities in a common gateway is not an easy task, and this trouble is increased in multi-purposed buildings with very variable occupancy and increasingly diversity of uses, such it occurs with Museums. In this work, we develop a functional approach which follows a typical workflow consisting of 1) identifying needs (in specific environments), 2) evaluating available infrastructures (equipments and systems, available sensors), 3) modelling interaction, 4) designing integrated solutions, 5) implementing and validating solutions. We propose a scalable solution based in commercial autonomous devices with minimal wired devices, which is surveyed by a typical Services Oriented Architecture (SOA) with a communications module (including alerts and eemergencies management), and tools for information processing and analysis. By security reasons, all services are embedded in an Intranet with monitoring and remote control which are managed by a Web server. This solution is being considered for its application in a Spanish Museum.

Keywords: Energy Efficiency, Integrated platform, SOA, Cultural Heritage, Museum

1 INTRODUCTION

Energy Efficiency can be defined as the consumption reduction by preserving similar energetic services, without lowering comfor and life quality, and by warrantying a sustainable behaviour in its use. From the early nineties and due to the increasing energy costs and higher responsability in regard to environmental conditions, systems and equipments have improved their efficiency in increasingly complex environments. Main objectives for Energy Efficiency in Museums (EeM) concern to the reduction of conditioned air, heating store or heating exchange with environment, the control of CO_2 emissions and distribution of gases involving oxygen or ozone in indoor environments, or their reduction by the use of CFC or HFC linked to conditioned air. There are different devices, including some commercial solutions for several of the above aspects, but currently there is no an integrated solution, neither modular solutions for related data mining. Our limited knowledge has institutional and technological aspects.

Institutional aspects are related to some defficiencies in harmonization of directives, a very limited information about meaningful cases of use for sharing experiences, and some renuences from the side of cultural entities for adopting more advanced technological solutions due to budget limitations or risks for artworks. From the institutional viewpoint, changes in the European Directive in Construction 2002/91/CE, have been reflected in the Spanish legislation for construction section. These changes involve to energy consumption, lightening, isolation, heating, climating, and an increasing use of renewable energy sources (solar, photovoltaic, wind, biomass). Energetic certifications try of giving a quantitative measure of the above factors, by assigning relative weights in models which unfortunately are not enough accurate. In Spain there are a collection of legal directives which intend to give a response to increasingly hard requirements and involving to the Technical Code of Construction (Código Técnico de Edificación or CTE), Modifications of Directives of Thermic Installations in Buildings (Reglamento de Instalaciones Térmicas en Edificios or RITE), Updating of the Directive of Thermic Isolation (Normativa de Aislamiento Térmico NBE-CT-79), Energetic Certification of Buildings (Certificación Energética de Edificios or CEE), Action Plan for Saving and Energetic Efficiency and a Promotion Plan of Renewable Energies (Fomento de Energías Renovables). A so large diversity of directives is a bottleneck for harmonisation between different agents and its interaction in a global market.

Between technological aspects there is a lack of a common methodology (involving universally acknowledged models) and the lack of interoperability between different solutions. In this work, we develop a methodology to improve Energy Efficiency in Museums. Most Spanish Museums are located in Cultural Heritage buildings which pose very specific problems to improve Energy Efficiency from conservation viewpoint. Hence, phyisical interventions must be minimally invasive, whereas monitoring and tracking of ambient conditions are crucial for designing and implementing solutions able of recovering a balanced behavior of buildings along the interaction with visitors. Currently, Museums are not only a collection of exhibition rooms but multicultural centers including temporal expositions, and rooms for research, learning and recreative activities, also. Their polivalent character poses new challenges for Optimal Energy Managment. From late nineties, environmental conditions of public and store areas, have become the most important factor in regard to conservation of artworks belonging to the Museum. Modifications in parameters relative to contamination (chemical products, vibrations), humidity, temperature and lightening can deteriorate or produce irreversible damages in cultural goods which are contained in Museums. Thus, conservation policies must have a preventive character with respect to unappropriate ambient conditions.

Some classical solutions: In this work, we are focused towards public spaces where environmental conditions display a higher degree of variability and can require a higher interaction in regard to installations, equipments and systems to compensate external variations of temperature or humidity typical of continental climates. Nowadays, the accent is put on climatisation improvements with minor energetic costs, instead of heating and cooling, which require a high contribution from the energetic viewpoint. In other words, our approach is nearer to exergy concepts to minimize losses due to increasing entropy. This viewpoint implies some changes in environmental design for reducing energetic consumption, without sacrifying comfort conditions in indoor public spaces. Some advantages which are linked to the implementation of a right environmental design are the following ones:

- Reduction of conditioned air, which is specially meaningful along summertime.
- Reduction of heat repositories and energy generation.
- Lowering of undesirable gases concentration, not only CO_2, but also another gases linked to refrigerants of conditioned air (CFC or HFC e.g.) or related to manipulation of residues.
- Minimization of effects linked to urban heat islands.
- Improvement of comfort conditions and lowering of PDP index (percentage of disagreed persons).

A balance between external and internal environmental conditions minimizes the amount of requirements for equipments and systems. Classical solutions involve to outdoor vegetation. In particular, the existence of green spaces or internal patios, including traditional devices as water pools or heat sinks, improves the local mircolimate and reduces damages linked to adverse environmental conditions and, consequently, a reduction of refrigeration needs. In particular, outdoor vegetal barriers at South façades offer a natural protection of solar radiation and cooling by evaporation along the summer, at the same time the allow a higher insolation along the winter. Furthermore, external vegetation creates a barrier against the wind which reduces differences due to the air pression in the buildings surface whcih modifies the interaction between the building envelope and the outside. Unfortunately, this cheap and classical solution can not be applied in a large number of Spanish Museums which are located in historical urban centers, where it is not possible modify the environment to develop substantial modifications.

Other classical solutions are linked to natural ventilation, mainly by night along the summer. Ventilation is based on the air movement which is produced from heat extraction along the interaction with another objects (including human beings) as a consequence of evaporation. The use of hybrid systems given by solar air heatings and heating systems offer a cheap alternative to conditioned air. However, a strict control of pollutants arising from outside is necessary to avoid damages at exposed artworks

2 ENVIRONMENTAL PARAMETERS INVOLVING HERITAGE PRESERVATION

From the physical domain viewpoint, a large number of Museums are located in historic buildings.

In this case, interventions are strongly limited by Cultural Heritage needs for conservations and preservation relative to exposed works and built environment. This fact poses specific characteristics relative to models, processes and applications involving container and contents, by balancing needs of context and users. Current solutions involve to Humidity (H), Atmospheric pollution (AP), Noise and vibration (NV), Temperature (T), and Lightening (L). There exists already, some commercial integrated solutions involving HVAC(Heating, Ventilation, Air Conditioning), and their interaction with temperature. These solutions allow a continuous improvement of performance of solutions with a feedback between an increasingly larger number of control points for monitoring, data mining procedures, feedback control and operations units. However, these solutions are not enough, and it is necessary to integrate another kind of sensors, controllers and actuators in a common gateway to improve the (commonly unvoluntary) interaction of human beings with highly risked environments, such those of Museums. In this section we gve a description of main parameters which we must have in account for Cultural Heritage conservation in an indoor environment.

2.1 *Relative humidity*

Regarding relative humidity in an indoor environment of a Museum there are three principal categories for deterioration evaluation of object which are in exposition:

a. Changes (often microscopic) at size and shape of exposed objects: the presence of absence of humidity is responsible for moisture particles, which can be accompanied of destruction of artworks.
b. Changes in deterioration rates of Chemicals reactions involving different categories:
   - Apparition or acceleration of corrosion at metals;
   - Disparition of pictorial pigments at different polychromed materials (paintings, sculptures, cloths, etc)
   - Lowering of paper or another support for paintings
   - Deterioration of specific materials (wood, glass, ceramics, stone).

A relative humidity higher to 70% propitiates the moisture development which can be more dangerous effects in presence of hot ambient with static air. Development of bacteria requires the presence of high relative humidity. In some cases, microscopic elements are the best indicators for behavior of specific materials regarding relative humidity.

2.2 *Atmospheric contamination*

Is perhaps the most important menace for preserving collections in a Museum. The apparaition of atmospheric contaminantssuchas sulphur and nitrogen, oxides, and other particles, and their ability for deteriorate exposed materials, or even modify the composition of indoor gases (ozone and oxigen, mainly) is a very important component in preservation issues.

2.3 *Noise and vibrations*

It is necessary to avoid the construction of museums near to acoustic contamination sources. The allowed noise rate is 35 NR. In urban environments, noise can be produced by traffic of vehicles, the prsence of sources of acoustic contamintation near to the Museum, construction works in nearby zones, air conditioned or cleaning systems noise, and massive affluence of visitors. Noise and vibrations can produce damages in artworks (including destruction for fragile objects such as glass, e.g.) in unstable conditions, or malaise for visitors.

2.4 *Temperature*

Temperature in areas of exhibition and store in Collection of cultural contents is the third most important factor for deterioration análisis, just after humidity and environmental contamitation. Emperature increasing in Museums can be the responsable for a Collection of reactions such as

- The acceleration of chemicals process of materials degradation. By example, when temperature grows from 15ºC to 20ºC, corrosion rate of cellulose increases around un 250%. It can produce the acceleration of natural processes such as water and air movements.
- Expansion/contracton of exposed materials.
- Partial drying of proofs (wood, paper, cuero et al) can be in the origin of a fragility level for objects, mainly if relative numidity is ot preserved in a stable way.

Sometimes, an increasing of temperature inside Museums can be produced by a natural or artificial lightening. In the next subsection, we develop some basic issues relative to the (natural and artificial) lighening, and how to limitate their undesirable effects.

2.5 *Lightening*

Deterioration of materials requires energy. Light is the most powerful of energy in Museums, and lightening represents different kinds of interaction of light with matter. However, illumination systems do not involve to AEC aspects, and because of this they will not be considered in this work.

3 HVAC SYSTEMS

Heating, Ventilating and Air Conditioning (HVAC) is a set of methods and techniques which are focused towards properties of air to improve quality and comfort at indoor environments for each room. Most of software solutions are applied to the whole building, and there is a very limited information about desaggregated systems for rooms or flats. HVAC systems can include different equipments or subsystems which are linked to cooling unities, air management systems, or heat pumps, between others. Main functions of HVAC systems are related between them and must fulfilll usual requirements relative to economic aspects (cost-benefit analysis) relative to installation, operation and management costs. General principles and prerrequisites for HVAC systems for Museums are the same as for ordinary buildings, i.e., they involve to ventilation, reduction of air infiltration and maintenance of adequate levels of pression beteen spaces. Usual methods involve to each system in a separate way; very commonly, exchange effects between different components and more recent hybrid systems, such as heating with low-temperature radiant heating systems and solar systems, are ignored. Their integration in systems able of identifying exchanges between different components must be performed in the Exergy framework to achieve a better understanding of exchanges between different energy sources and environmental issues. However, this integration requires a change in mind and a simplification of current developments in order to be appliable far away from the academic world.

Traditional functionalities for internal control Museums are focused towards satisfying the need of optimal conservation of expositions, and satisfaction of personnel and visitors needs in terms of comfort and heatlhy conditions. They involve to environment and users. The choice of best option for ambiance control in Museums is more complicated in Museums than for ordinary spaces. Alternance between quite different spaces, low monitoring for ambient conditions and a very variable range of occupancy, and, consequently, of interaction between human and environment make some difficult the optimal choice of best option for HVAC. This problem can be posed as a combination of different factors or criteria involving 1) economic issues (cost-benefit analysis), 2) impact on a very sensitive Cultural Heritage environment, and 3) resolution of comfort and efficiency requirements according to a sustainable perspective.

Following this viewpoint, one must solve a Multicriterion Decision Problem having in account structural aspects of building, equipments and systems and personnel satisfaction. The combination of all these three components conditionates the relative weight for each criteria which depends on priorities, the current state of buildings, and equipments and systems (to be incorporated or already available). Unfortunately, there are no enough cases of use which can illustrate which are the most appropriate weights depending on type of Museums, nature of collections or enviornmental conditions for making easier the choice of the best option. In the meantime, it is convenient to identify which are the most appropriate subcriteria allowing to decompose each criteria in several subcriteria having in account viable solutions for each environment.Currently, there is no still an integrated solution for all of them. From modelling viewpoint and following an increasing coarse-to-fine approach, it is convenient to start with a linear programming approach where each component is weighted according to constraints of building, goals and required functionalities.

From technical viewpoint, some low cost solutions relative to equipments and systems involve to a) Mechanical Ventilation Systems which are operated by means of the opening of upper windows for creating air movements; b) large windows at South façades to improve building heating by means of solar radiation; c) solar or photovoltaic pannels at penthouses for energetic store. More advanced solutions from technological viewpoint involving to systems and equipments to be considered are related to a) Trombe walls (for creating air ventilation between opposite façades due to the temeperature gradient), or b) Intelligent materials (including materials at façades with "memory" to store energy along the day which is returned to the indoor ambient along the night). From IST viewpoint, it is necessary to advance towards a semi-automatic control in terms of the interaction between human beings and very sensitive environments, such those corresponding to Museums.

4 INTELLIGENT CONTROL SYSTEMS: BEMS

The integration of intelligent components contributes to satisfying environmental requisites in a more complex, but also more efficient way. Nowadays, there are several commercial control systems which integrate functionalities in sevral domains relative to a) thermic control, b) lightening and solar radiation control or c) air quality and ventilation control.

Building Energy Management Systems (BEMS) integrate and manage a large number of sensors (ordinary HVAC systems, fire alarms, smok ventilation, security), depending on needs and requirements. A BEMS allows to save energy without sacrifying comfort. The diagram of any intelligent control system follows a typical Services Oriented Architecture (SOA), including 1) a module of monitoring (for sensors and actuators), 2) a communications module for data exchanging between different components, and 3) an information processing and analysis module. The three above modules are interconnected between them; in particular, signals and commands represent communications between monitoring modules and "smart" devices. Results are stored in a data mining module which will allow in the future the patterns identification in terms of the interaction between the physical environment and users.

Sensors measure environmental parameters which are necessary for control strategies, including indoor and outdoor temperatures, air quality (CO_2, ozone, presence of another gases), velocity and direction of wind, weather conditions (rain, solar radiation, e.g.), humidity, etc. All of them can be used for managing each room or zone according to physical models.

Next, we shall explain the use of a simple architecture for control systems involving sensors and actuators which is being examinated for a National Museum in Spain. Before describing them, let us remark that an exact measurement and a temperature control can imply a energy saving around 5–10% in a building which has been reconditioned recently; this is not a very meaningful amount in regard to the objectives of the European Commission, but if one compares with the relatively low cost of the control system, this saving is meaningful for a large Museum.

Building sensors (mainly for HVAC parameters) are located at indoor and outdoor. They send the information to the controller which interpretates and rules the climatization system through actuators for adjusting ambient conditions according to the above prerrequisites. Some devices of common use for controlling humidity levels are used for humidifying (heating, atomizers, evaporation and quick ventilation) or deshumidifying (by condensation or by absorption).

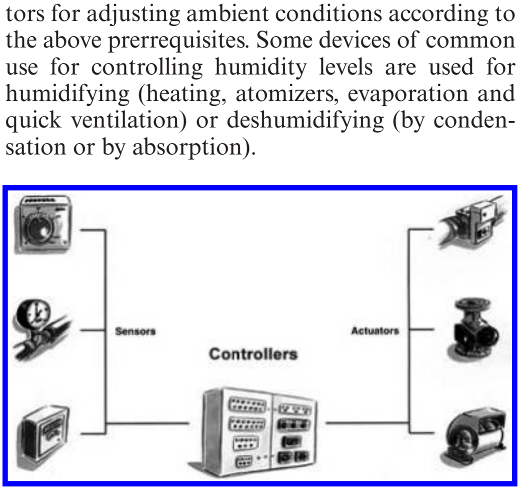

Figure 1. Schema control system.

- Measurement and control of humidity are very useful for Museums, specially in installations with ventillation systems of variable flow. Humidity data can be obtained from the mechanic ventilation system for adjusting working modes of the system, according to prefixed environmental conditions, and for preserving conservation prerrequisites.
- Illumination control is performed in terms of time controllers, occupation sensors and photsensors which help to reduce excessive lightening consumption in expositions.
- Ventillation control intends to maintain the control of conatminants concentration to an admisible level by menas of traditional solutions (opening windows in upper parts) or more innovative solutions (networks of internal ventillation conductions). Sensors for air quality control are designed for identifying a large amount of gases and toxines.

5 CONCLUSIONS

The main problem regarding Energy Efficiency in Museums concerns to the physical environment. A so restricted scenario imposes constraints relative to the optimal combination of equipments and systems, for measuring and controlling interactions of the Museum as a container of artworks with visitors. There is no an universal solution for finding an optimal solution, but the right framework would must be given by some Multicriterion Optimisation. In the meantime, we propose the use of usual Linear Programming for solving optimality issues. The optimal management for energy efficiency in Museums is linked to the control of parameters involving signals and commands, which are integrated in a Services Oriented Architecture. Building Energy Management Systems (BEMS) and control systems for HVAC (Heating, Ventillation and Air Conditioned) parameters provide efficient systems for the building which allow to achieve meaningful energy saving in a short period. Regarding comfort, sensors for measuring air quality allow to balance temperature and humidity, and to detect other gaseous components. Their combination with photosensors (including the most efficient LEDs by energetic saving) and occupation sensors cover main requisites to improve surveillance of artworks surface under stress conditions due to lightening and visitors interaction.

ACKNOWLEDGEMENTS

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Best Practices in ICT enabling energy-efficiency in the built environment

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ABSTRACT: This paper presents the work achieved in the context of the European REEB project to identify Best Practices regarding the use of ICT applied to energy efficiency in buildings throughout Europe, and select the most representative practices as detailed examples. Selected practices are described in terms of concept, impact, involved stakeholders, level of development, and dissemination and future trends, with the objective to synthesize information covering the integration of human, organizational and technical elements for ICT-based energy efficient buildings. The objective is to enhance awareness of Best Practices exchange and the capabilities of the construction sector.

1 INTRODUCTION

The building sector is the largest resource-consuming sector: residential and tertiary buildings are responsible for about 35% of the EU's total final energy consumption and GHG emissions (see below Figure 1). As a consequence, the sector offers the largest single significant potential for cost effective energy savings. This potential, if realized, would mean that in 2020 the EU will consume 11% less final energy.

It is today acknowledged that ICT have an important role to play in reducing the energy intensity and therefore increasing the energy efficiency of the economy, in other words, in reducing emissions and contributing to sustainable growth. As ICT is today pervasive to all industrial and business domains, it is expected to generate a deep impact in the energy efficiency of new or renovated buildings of tomorrow. Indeed, a lot of Best Practices already exist in this area, but in order to derive a comprehensive vision and roadmap of future RTD required to progress in the fields of an energy-efficient built environment supported by ICT, it is compulsory to first establish a state-of-the-art based on already existing Best Practices.

This work has been undertaken as part of the REEB project (European strategic research Roadmap to ICT enabled Energy-Efficiency in Buildings and construction—EC-funded Coordinated Action—http://www.ict-reeb.eu) for ICT to support energy efficiency in the built environment: REEB aims to drive progress in future RTD supporting the transition to an energy-efficient economy and a sustainable society, and in ICT to facilitate the transition to energy-efficient, low-carbon buildings and cities.

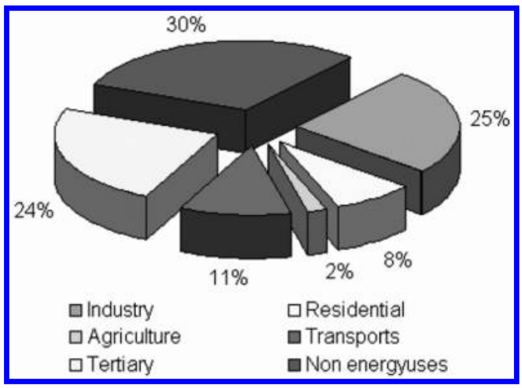

Figure 1. Final energy consumption by sector (EU-27 2007).

2 OBJECTIVES

The aim of this work was to elaborate a guide of the most representative current Best Practices with regard to the human, organizational and technical aspects in relation with the use and deployment of ICT applications and tools for energy-efficiency in construction. More precisely the objectives of this guide were:

– To collect and synthesize information covering the integration of human, organizational and technical elements for ICT-based energy efficiency in the built environment, in order to enhance awareness and exchange of Best Practices, and the capabilities of the construction sector;
– To promote a basis for future dialogue with people who are active in similar areas or who otherwise are interested in the issues of REEB;
– To serve the industry at large and SMEs in particular in the form of a set of guidelines towards migration to and adoption of state-of-the-art methods and tools.

3 APPROACH AND METHODOLOGY

As a first step, this task aimed to provide a comprehensive identification of functionalities and associated criteria for selection of Best Practices considering ICT-based Energy Efficiency in Construction, including aspects related to business processes and information management practices, with the objective of identifying the today most exemplary scientific approaches and (industry) business processes. In a second step, it aimed at elaborating a guide of the most representative current Best Practices with respect to the human, organizational and technical aspects in relation with the use and deployment of ICT applications and tools for energy-efficient buildings.

It was first decided to make a clear difference between "case studies" and "Best Practices". In the context of REEB, case studies were examples of the current state-of-the-art use of ICT applied to energy efficiency improvement in building and construction, while Best Practices were generic, but detailed, cases considered as most representative practices.

The identification and selection of Best Practices then consisted in four different phases:

– Elaboration of an harmonized categorization of ICT tools and systems to support energy-efficient buildings;
– Creation of a "Best Practice description template" using the previously defined harmonized categories, to be sent throughout Europe (and especially to all members of the International REEB Community), in order to collect case studies about the use of ICT for energy efficiency in buildings;
– Analysis of the collected case studies and identification of "clusters" or groups of case studies dealing with similar concepts, applications or technologies;
– Derivation of generic Best Practices from the identified clusters.

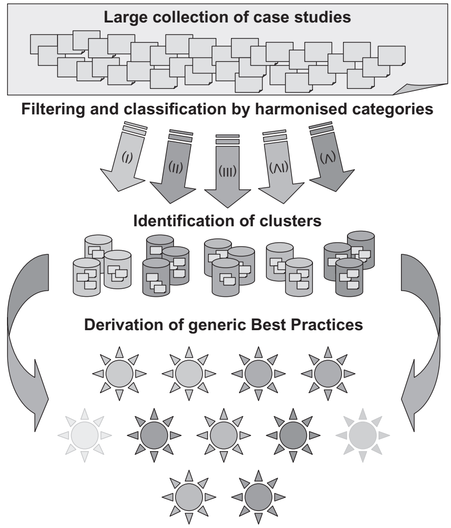

Figure 2. Methodology used to identify Best Practices.

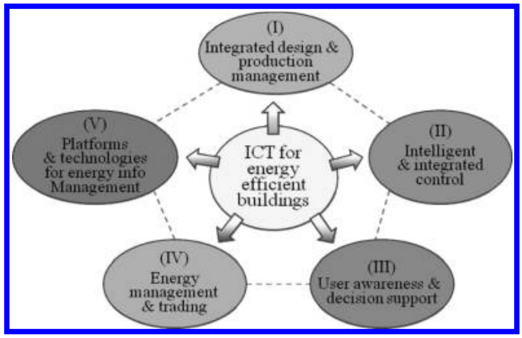

Figure 3. Main REEB classification categories.

3.1 *Harmonized categories*

The selection of Best Practices first required the identification of a set of criteria, or characteristics, to collect and classify the Best Practices examples provided under the form of case studies. Five harmonized classification categories were finally selected, as shown below in Figure 3.

3.2 *Best practice description template*

Each collected case study was described using a two-pages template allowing to get information on the ICT applied in this case study, the type of building, the stakeholders, the impact, the innovative aspects, and the attached REEB categories.

3.3 *Case studies analysis and clustering*

88 case studies have been collected through the previous template, ensuring the REEB consortium

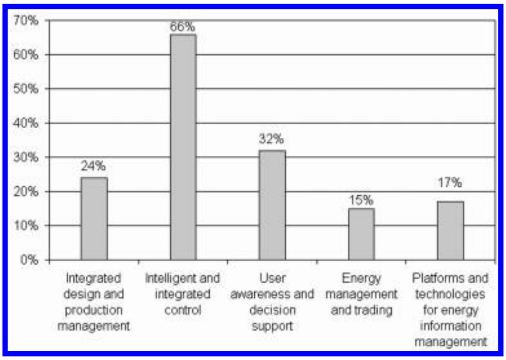

Figure 4. Distribution of case studies per REEB category.

to have a rather representative set of different practices in terms of ICT use for energy efficiency in buildings—with a business focus of those case studies targeting resource efficiency and clean buildings, innovative components (with embedded devices) & software for new buildings, insulation improvement, installations enhancement (in relation to heating, ventilation, hot water, …), renewable energies integration, etc.

Figure 4 shows the distribution of all case studies per main REEB category.

The REEB consortium decided not to draw extensive conclusions from the distribution of case studies among categories. Whether the pre-eminence of the "Intelligent and integrated control" category reflected a market fact or was due to a bias in the contributors sample, it has not been investigated. The reason was that the results of this analysis shall not be considered as a market survey.

Further analysis of the collected case studies then led to the identification of 16 "clusters", which themselves permitted to select a first set of 12 different Best Practices.

3.4 *Generic Best Practices*

The previous clustering of case studies led to the identification of 12 generic Best Practices:

- Simulation based energy design
- Early energy design
- Integrated solutions based on BIM
- Smart metering for energy consumption awareness
- Building Management Systems
- Wireless sensor networks for energy performance monitoring
- Standards based energy performance assessment software
- Energy performance audit solutions
- Websites for collecting and disseminating energy efficiency "good practices"
- Smart Grids
- Standards based solutions for building life-cycle management
- Standards-based energy data exchange solutions

4 EXAMPLE OF GENERIC BEST PRACTICES

We give hereafter an example of Best Practice related to Building Management Systems.

4.1 *Scenario*

Mr. Jones is the facility manager of a complex building of about 10 000 m^2, with offices, meeting rooms, a company restaurant and 500 daily users. Mr. Jones is a happy man: about one year ago, he convinced his boss that there was a huge potential for energy (and money) savings if a Building Management System (BMS) was installed in the building. And today, the actual figures confirm what he and the supplier of the system presented at that time. Although the cost was not negligible, the return on investment is now confirmed to be less than 3 years.

The BMS is now connected to the heating, ventilation and air-conditioning systems, to many active components in the building (lights, shutters, fans, etc.) and to a lot of various sensors (presence, temperature, humidity, light, etc.). Integration of the system to the existing installation was easy because of the high compatibility with other commercial solutions.

Currently it is winter, and the sun is shining: unoccupied south-facing meeting rooms shutters are left open, in order to maximize solar gains and avoid using the heating system as much as possible. However, when people enter the meeting room and manually overcome the automatic control, requesting the shutters to be closed (because they need to use a beamer for their meeting), the system adjusts the light to the needed level, starts up heating and adjusts the ventilation rate. When the meeting is over and people leave the room, the presence sensors send the information and the system falls back to the standard setup.

The photovoltaic panels (installed on the building's roof) are also monitored by the central system. The use of the electricity generated by these PV cells is privileged by the BMS (for lighting, other electrical office appliances, etc.) when it is available. It has been sized to cover a good part of net electricity requirements for the whole building.

Maintenance is easier, too: this morning, the system detected an unusual low value for the heat pump's COP (coefficient of performance), probably due to a pressure drop in one of the heat pump's compressors. The system then started the natural gas boiler, bypassing the standard setup that gives the priority to the heat pump when the outside temperature is above 5°C. At the same time, the system switched on an alarm on the central display and sent a mail to the maintenance company, warning that a failure has been detected in the heat pump and that the COP was not at the expected level.

From the central monitoring display (available through the internet, on his laptop at home or on his smartphone), Mr. Jones has a full access to the whole system, to all energy consumption balance sheets and can easily adapt the global strategies, considering the system's suggestions based on past and future trends identification.

Mr. Jones is definitely a happy man.

4.2 *Short description*

Building Management Systems (BMS) are central computerized systems for managing and operating various equipments within a building. BMS usually incorporate controls for air conditioning, heating, cooling, ventilation, lighting, energy production and storage, maintenance management, security, access and fire systems.

BMS is also known as BAS (Building Automation System), EMS (Energy Management System), or DDC (Digital Direct Control).

4.3 *Concept*

A BMS (Building Management System) is a computer-based control system that is connected to the building's mechanical and electrical equipments such as heating, cooling, ventilation, lighting, and even insulation and appliances, in addition to power systems, fire systems, and security systems. An advanced BMS also has the ability to control the building's energy production and storage systems (photovoltaic panels, combined heat and power generators, batteries, etc.) along with the possibility to retrieve information from the Internet, like weather forecasts.

It uses a combination of:

– Wired or wireless sensors (for occupancy, movement, light fluxes, internal solar radiations, windows and doors states, blinds, indoor/outdoor conditions such as temperature, humidity, CO_2, air quality, etc.);
– Actuators (for heating, cooling, ventilation systems, blinds, doors and windows, lights, energy production equipments, etc.);
– Meters (for water, air flow, and all kind of energy: heat, electricity, gas, etc.);
– Centralized or distributed/embedded intelligence software, for activity monitoring, timetables implementation, optimisation algorithms and user interfaces (real-time data display, alarms, remote control features, etc.);
– A central communication network using proprietary or open-standards protocols (e.g. DALI for lighting, TCP/IP, BACNet, Lonworks, KNX or Zigbee …).

4.4 *Provided service*

The main goal of current BMS is to control all energy components of the system in an optimised way to minimize global primary energy consumption while ensuring optimal indoor comfort (according to user needs and wishes) and safe operation of all controlled equipments, based on three main functions:

– Advanced monitoring (including maintenance supervision, failure detection, diagnostics);
– Optimised control;
– Real-time and consolidated reporting (including benchmarking features).

Through the use of optimisation algorithms (based on neural networks, fuzzy logic or genetic algorithms), a BMS computes all collected information (from sensors, meters, actuators, micro-chips and embedded systems) and provides an efficient and optimised control of all active equipments in a building. To manage energy use, it can monitor various parameters in the building such as temperature, humidity, energy usage and occupancy patterns. By doing so, services such as air conditioning, ventilation and heating, lift services, hot water systems and lighting are able to be controlled in ways that minimize energy use while optimizing comfort and functionality. Most advanced systems can mix activity information (level of human activity, in order to set the internal conditions according to the level of activity of the users), weather forecasts (link to the Internet), indoor and outdoor conditions (temperature, humidity, air quality, etc.) and information coming from all connected devices (status, alarms, consumption …). The optimisation is based on schedules (time of day, day of week, holiday periods), presence information, external weather conditions, user wishes collected through human-machine interfaces, and on the building's behavior. A lot of the needed information is provided during the installation and first set-up phase of the system, but a BMS is of course reconfigurable according to the potential changes in the building's configuration and usage.

A BMS also features reporting capabilities, and can inform the users, energy managers or building owners about the status of the building in real-time, in terms of energy global or detailed consumption, status of all connected devices, equipments and systems.

A BMS is a very important tool in tuning the operation of current buildings (especially the large and complex ones), and becomes essential in the operation of high-performance or positive-energy buildings, because of the need to precisely balance the behavior of all components (energy production, consumption or storage) in the building.

By controlling the energy production and storage systems in addition to the "standard" HVAC equipments in a building, a BMS is a key element for the building to be connected to a "smart grid", an intelligent energy network that takes advantage of interactions between the energy providers and end-users, where consumers become "prosumers" (producers-consumers).

4.5 *Impacts*

By controlling up to 70% of the energy use in a building, BMS using efficient algorithms can lead to improved comfort in buildings while reducing energy consumption. This ensures that operating costs are minimized and occupants are more comfortable.

Since every building is different and all kind of configuration can exist, it is difficult to precisely predict how much energy savings can be achieved through the integration of a BMS in a building. It is generally admitted that the energy savings can range from 10% to 40% compared to the same building without a BMS, while maintenance costs are reduced by 10% to 30%.

4.6 *Stakeholders*

In the BMS market, current stakeholders are:

– Building tenants/users/occupants
– Building owners, renters
– Building managers (operations/facilities managers)
– Maintenance companies
– Energy providers/distributors

In the near future, new stakeholders could appear:

– Architects / design teams
– Planners

Current providers of BMS are either big companies or SMEs.

4.7 *Maturity*

A quick market survey shows that lots of commercial offers exist, but no standard applies to BMS solutions. Every building is a one-of-a-kind and a BMS has to be finely tuned to the precise building it is installed into.

In term of commercial offer, two levels have been identified: most of the time smaller companies tend to provide smaller scale solutions (for individual or small collective residential buildings), while big, international companies are selling solutions that apply to large and complex industrial, commercial or office buildings or even groups of buildings.

The concept of BMS applies to a lot of different applications, from the simple integrated and intelligent HVAC operation system or smart lighting system, to the full-featured optimised application described in the previous sections, connecting all energy devices in a building, from lights to HVAC, along with lifts, security and energy storage and production equipments.

Most of current systems only provide part of the described services, and the trend is to evolve towards fully integrated systems, connecting more and more active elements in a building.

4.8 *Current level of dissemination*

While the concept of Building Management Systems is quite widespread, the usage is not, especially in smaller buildings. In addition, it is worth mentioning that, for large installations, the most current situation is still to have independent subsystems (controlling HVAC, lighting, etc.) that do not follow a holistic and systemic approach.

However, Building Management Systems tend to be more and more common in recent complex industrial, commercial or office buildings, which consume huge amounts of energy and where efficiently operating all energy devices in a building becomes too complex to be done manually or with traditional methods and recipes.

Moreover, a BMS adds value to the building it operates (because of better energy use, ease of operation and maintenance). In consequence, the use of BMS is spreading faster in private-owned buildings than in public ones.

4.9 *Future trends*

Future developments (short, middle and long terms) of BMS include:

– More integrated systems, taking into account more and more components and equipments in a building (this aspect requires a higher level of interoperability between sub-systems);
– Closer interaction with the energy network—capacity to control energy use in the building depending on future energy costs, anticipate higher costs and store energy (heat, electricity) using batteries or thermal mass;

– Energy benchmarking features: compare the building with similar buildings (introducing ranking possibilities), history of energy consumptions;
– Disaggregate end-use consumptions (get detailed views separated for HVAC, lighting, by floor, by room, etc.);
– Integrate widespread energy communication standards for energy devices (consumption, production and storage) and controllers (sensors, actuators) interconnection;
– Use prediction to reduce the number of sensors connected to the control network: i.e. extrapolate data obtained for a room equipped with sensors for similar rooms;
– Link BMS with design phase (e.g. link with BIM);
– Connection with external services and interfaces with stakeholders (e.g. billing system interfaced with BMS in case of a hospital).

5 CONCLUSIONS

The Best Practices identification process that has been put in place by the REEB consortium permitted to collect 88 different case studies of ICT solutions applied to energy efficiency in Building and Construction. Through the International REEB Community (IRC), a large number of European and worldwide ICT, Energy and Building & Construction players contributed to this effort.

Based on the large number of collected case studies and the various natures of contributors, the REEB consortium considered that the final collection contained a wide variety of different cases, giving a good overview of current practices about ICT-enabled energy efficiency in Building and Construction.

The 16 clusters that were derived from the case studies collection led to the identification of 12 generic Best Practices that have been gathered in a "Best Practices Guide", released in April 2010.

The Guide was intended to be used as a basis for additional work in the REEB project, as well as a stand-alone booklet about reference practices for use of ICT applications and tools for energy efficiency in the buildings and construction sector, in Europe and worldwide.

ACKNOWLEDGEMENTS

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Process modelling of industrialized thermal renovation of apartment buildings

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ABSTRACT: With the "Grenelle 1" law, the French government set the goal to retrofit 400,000 dwellings per year from 2013, of which 70,000 social dwellings. However, artisanal methods will not enable to reach these goals, because of the lack of productivity of building industry firms. A new industrial process must be proposed to offer a thermal renovation at low cost, in a short time, with high quality and good environmental balance. It is the mission of the SIRENE research project (Industrial systems for thermal renovation) whose objective is to industrialize the renovation of apartment buildings. In this paper, a process modelling of industrialized thermal renovation of apartment buildings is presented with IDEF0 diagrams. A focus is made on one of the most important activities: the preliminary study of the existing buildings.

1 INTRODUCTION

1.1 *Retrofit the existing buildings to save energy*

In several countries, research works are carried out on the efficient measures to take to reduce energy consumption of the building stock. Most states set regulations to improve the energy performance of new buildings. However, the annual rate of construction of new dwellings is only 1.1% in Europe (Poel et al. 2007). It is therefore very important to retrofit the existing buildings to really reduce the energy consumption of the building stock. Ouyang et al. (2009) presents an overview of the international scientific literature in the field of energy-saving renovation measures for residential buildings.

1.2 *The building sector, first consumer of final energy in France*

In France, the building sector is the first consumer of final energy with 68 millions of tons of oil equivalent (42.5% of the total final energy). Moreover, it produces 123 millions of tons of carbon dioxide per year (23% of the national emissions) (Minister of Ecology, Energy, Sustainable Development and Sea 2009). Note that final energy is energy that is delivered to consumers: electricity, gas, diesel fuel, domestic fuel, etc. whereas primary energy is energy found in nature that has not been subjected to any conversion or transformation process. The difference between these two types of energy is the energy required to produce, to store and to distribute final energy from primary energy.

There was a total of 31.5 millions of dwelling units in France in 2008. Their conventional primary energy consumption is presented according to types of residential buildings in Table 1. In the building sector, the conventional primary energy consumption corresponds to the primary energy consumed for heating, cooling, hot water production, ventilation and lighting of the building for one year. Its unit is the kilowatt-hour per m^2 per year (kWh/m^2/year). The considered area is the "Surface Hors d'Oeuvre Nette (SHON)", which is approximately the Net Floor Area (NFA).

In social housing, 85% of the dwellings are multi-family dwellings and 15% are one-family dwellings.

1.3 *The ambitious goals of the "Grenelle 1" law*

Following the "Grenelle de l'environnement", the "Grenelle 1" law aims to reducing the energy

Table 1. Mean annual consumption of primary energy according to types of residential buildings (Marchal & Lagandré 2008).

	Number of dwellings	Mean consumption of primary energy
	Millions	kWh/m^2/year
Single-family houses	16.6	298
Private apartment buildings	10.4	273
Social housing	4.5	199

consumption of the existing buildings of at least 38% by 2020. Therefore, the French government sets the goal to fully retrofit 400,000 dwellings per year from 2013 (Legifrance 2009). This goal is detailed for social housing: the 800,000 social dwellings whose annual consumption of primary energy is higher than 230 kWh/m^2/year will be retrofitted by 2020 to reduce their consumption to less than 150 kWh/m^2/year. Therefore, 70,000 social dwellings should be retrofitted per year from 2011 (Legifrance 2009).

1.4 *Not enough dwellings are currently retrofitted*

In 2006, 9,110,000 private dwellings underwent maintenance or renovation works, of which 4,890,000 related to works on the roof, the openings, the inside of the dwelling or the heating system. Among these, 2,520,000 renovations (including 2,020,000 of single-family houses) had real opportunities for improving their energy efficiency. However, only 100,800 dwellings underwent a complete renovation, that is to say a simultaneous renovation of the opaque walls (roof or interior), the openings and the heating (Trotignon et al. 2008).

As far as public housing is concerned, the goals related to the dwellings renovation were defined by the law No. 2003-710 of 1st August 2003, which establishes the National Urban Renewal Programme (PNRU). Between 2004 and 2013, the demolition and reconstruction of 250,000 dwellings is planned, as well as the "residentialisation" of 400,000 dwellings and the renovation of another 400,000 dwellings. On the 31st December 2007, the renovation of nearly 220,000 dwellings is planned with the PNRU program and about 80,000 were started. Nevertheless only 44,000 dwellings were retrofitted between 2004 and 2007, including 18,000 in 2007 (Steering committee of the National Agency for Urban Renewal 2008).

The annual number of renovations is currently far too inferior to the targets of the "Grenelle de l'environnement". Besides, the social dwellings that are in the PNRU program show an important delay between the planning of the renovations, their start and their effective realization. According to the Steering committee of the National Agency for Urban Renewal (2008), several factors may explain this gap: "excessive optimism of the original planners, deficiencies of the owners and of the design offices, complexity of the ANRU (National Agency for Urban Renewal) administrative procedures".

To meet the goals of the "Grenelle 1" law, our research work aims to industrialize the thermal renovation of buildings with transferring the industrial engineering methods to the building sector. This paper presents in part 2 the general problem of the thermal renovation of buildings and the SIRENE research project (Industrial systems for thermal renovation). Then, in part 3, we propose a process modelling of the industrialized thermal renovation of apartment buildings, focusing on the assessment of the existing buildings' state. Finally, the conclusion of this research work and the perspectives of the SIRENE research project will be developed in part 4.

2 GENERAL PROBLEM AND SIRENE RESEARCH PROJECT

Nowadays, the building renovation is held back, not only because of its cost and time, but also because of the lack of skills of the building sector that do not succeed in providing high quality renovations on a large scale. The goals of the "Grenelle de l'environnement" will not be able to be met with artisanal methods of building renovation.

A new renovation process should be proposed to offer thermal renovations:

- at low cost,
- in a short time,
- of high quality,
- and good environmental balance.

It is the mission of the SIRENE research project (Industrial systems for thermal renovation) whose objective is to industrialize thermal renovation of apartment buildings. SIRENE is developed by the TBC Générateur d'Innovation company and ARMINES (Ecole des Mines d'Albi-Carmaux). This 3-year project is partly funded by the French Environment and Energy Management Agency (ADEME). After renovation, the targeted annual consumption of primary energy is 50 kWh/m^2/year, which corresponds to the standard new buildings require according to the French thermal regulation RT 2012 (Legifrance 2009). Among different possible technical solutions, the one that consists in adding an insulating envelope, which includes openings, external façade lining and other equipments such as air ducts, photovoltaic panels etc. outside the building drew our attention. One of the main advantages of this solution is the possibility to retrofit occupied dwellings without rehousing the inhabitants during the works and to prefabricate the components.

This research project focuses more on the industrialization of the renovation process than on the technical solutions for insulation. The building sector is indeed very dependent on artisanal methods, which are not always perceived as a quality guarantee, contrary to other industry sectors. The organization of the building site or renovation site is currently considered as not so important as the technical functions of the different building trades. Sacks et al. (in press) presents the requirements to develop a Building Information Modelling (BIM) based lean production management systems. Prototype interfaces were evaluated by construction companies but further research work would be necessary before disseminating the concept.

The tools and methods of industrial engineering are not so well known, except when it comes to planning and project management. The scientific literature is poor concerning the applications in the building sector using lean manufacturing tools (Value Stream Mapping, 5S, SMED, etc.) or more generally logistics and quality assurance methods.

However, the simple observation of a building site, whether it is a single-family house, a residential building or a commercial building, highlights some potential ways of improvement:

– disorders in materials and tools storage,
– many component cuttings and adjustments on site, with not necessarily appropriate tools,
– inadequate supply of components,
– waste,
– divisions of building trades and low flexibility of workers and technicians,
– numerous delays,
– numerous claims of owners …

From four case studies in Finland, Naaranoja & Uden (2007) identified common problems in construction projects and proposed improvements based on building trust, knowledge management and lean construction. Whereas industrial companies often have industrialization or organization and method services to prepare and organize work, building companies are mostly small. They often work "on demand" and rarely take into account the mass effect of their production. Each building is indeed unique but it is also the case of many industrial products that are manufactured in series.

Our research work aims to transfer the industrial engineering methods to the building sector in charge of the thermal renovation of apartment buildings in order to meet the workload (70,000 social dwellings a year to retrofit between 2011 and 2020). Before thinking about technological solutions, a preliminary study will be carried out to design and model a new process for industrialized thermal renovations. That will enable to identify constraints to design new components adapted to this renovation process.

In this paper, we will present what we consider as the first step of this work: a proposal of a process modelling of industrialized thermal renovation of apartment buildings.

3 PROCESS MODELLING OF INDUSTRIALIZED THERMAL RENOVATION OF APARTMENT BUILDINGS

3.1 *Aim of modelling*

The modelling aims to bring a comprehensive overview of the process we imagine for industrialized thermal renovations of buildings. Besides, it is very useful to consider the renovation process as a whole and to understand the interactions between the different activities.

To do so, the IDEF0 (Integration DEFinition language 0) functional modelling method has been chosen (National Institute of Standards and Technology, 1993). As a first stage and in the interest of clarity, we drew only the flows that are necessary modelling diagrams below. Then we will refine this modelling and add all the mechanisms and controls flows of the process.

3.2 *A-0 level: Retrofit one (or several) building(s)*

The top-level context diagram of the IDEF0 process modelling is shown in Figure 1. The main function of the renovation process is: "Retrofit one (or several) building(s)".

The control of this function is the goal set by the "Grenelle 1" law for social dwellings: to retrofit the 800,000 social dwellings which have an annual consumption of primary energy higher than 230 kWh/m^2/year by 2020 to reduce their consumption to less than 150 kWh/m^2/year (Legifrance 2009).

The input is one (or several) existing building(s) with its features such as its location, its year of construction, its type of dwellings (single or multi-family dwellings), its number of floors, etc. These features are used to decide whether the existing building(s) correspond(s) to the identified target of buildings: social dwellings in apartment buildings with simple general shapes and which can be a priori outside retrofitted. The historic buildings with architectural façades (for instance buildings

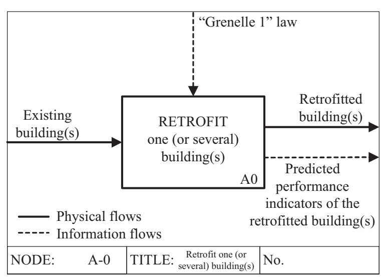

Figure 1. Top-level context diagram of the IDEF0 process modelling of industrialized thermal renovation.

with Haussmann façades) are not suitable to an industrial outside renovation. On the contrary, apartment buildings, for instance tower shaped, built after the Second World War and before the first French thermal regulation (between 1945 and 1975) are at the core of the target.

The use of a plural to refer to buildings is significant. Contrary to an artisanal process that is different each time, an industrial process is designed to suit many cases. Moreover, because of the important amount of buildings to retrofit, the mass effect will play an important role.

The output is one (or several) retrofitted building(s) and their related performance indicators: conventional indicators (calculated with a regulatory method) such as the primary energy consumption (in kWh/m^2/year) and the CO_2 emissions (in kg_{eqCO_2}/m^2/year) or more subjective indicators. For instance, we propose to define an "individual comfort indicator", which takes into account the different needs according to the type of occupants: for a same dwelling, an elderly person would require a higher heating setpoint temperature than a working couple with children.

3.3 *A0 level: Retrofit one (or several) building(s)*

The main function of the A-0 diagram is decomposed into four functions, represented in the A0 diagram of the IDEF0 process modelling that is in Figure 2.

3.3.1 *Assess the state of the existing building(s)*

The first function of the A0 diagram is "Assess the state of the existing building(s)". It consists in providing all the required information about the existing building(s) to study the renovation: the 3D model of the existing building(s), the performance indicators of the existing building(s) and the requirements of the renovation.

3.3.2 *Study the renovation of the existing building(s)*

The second function of the A0 diagram is "Study the renovation of the existing building(s)". It consists in designing the renovation according to the goals of the "Grenelle 1" law and the thermal regulation. The requirements of the renovation are converted into technical specifications allowing a high degree of prefabrication. The bill of materials is defined and the performance indicators of the retrofitted building(s) predicted.

3.3.3 *Manage the supply chain of the components*

The third function of the A0 diagram is "Manage the supply chain of the components". It consists in manufacturing the prefabricated components according to the bill of materials and carrying them to the building site. The production of the components obviously consumes raw materials and produces waste, but we chose not to represent these flows in the diagrams, in the interest of clarity. The components will integrate equipments such as electric wires, air ducts, etc. to reduce the work on site. The prefabrication of the components will enable to work in better conditions, to improve the quality control and to reduce the time and cost of the thermal renovation.

3.3.4 *Implement the components on the existing building(s)*

The fourth function of the A0 diagram is "Implement the components on the existing building(s)". It corresponds to the physical renovation on site. It consists in preparing the existing building(s) for

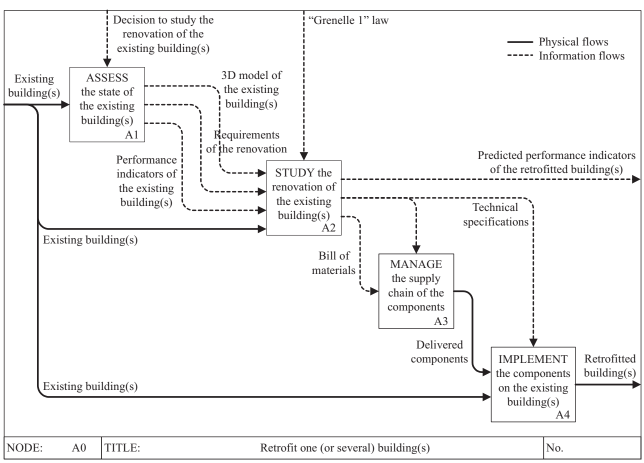

Figure 2. A0 diagram of the IDEF0 process modelling of industrialized thermal renovation with its four sub-functions.

the renovation, for instance by removing old items. Then the components are assembled and fixed on the building(s) and between them without rework.

3.4 *A1 level: Assess the state of the existing building(s)*

The function "Assess the state of the existing building(s)" is decomposed into three functions, represented in the A1 diagram of the IDEF0 process modelling that is in Figure 3. For an industrial process, this function is very important since the adjustments on site should be avoided. All the information required for the renovation must be collected and the potential constraints identified.

3.4.1 *Perform the 3D survey of the existing building(s)*

The first function of the A1 diagram is "Perform the 3D survey of the existing building(s)". It consists in taking measurements of the existing building(s) and creating its 3D model.

With a high degree of prefabrication, the components should be designed and manufactured with shapes and dimensions, which exactly match the existing building. Therefore, the geometry of the existing building, in particular it façades, should be known with precision: dimensions and position of openings (windows, doors, etc.) and balconies, façade projections, angular deviations, etc.

The required geometric information will depend on the chosen calculation method of the building's energy needs. In some cases, the two-dimensional (2D) drawings of the façades will be enough. In other cases, the three-dimensional (3D) model of the building will be necessary. The 3D model can be used to study several renovation variants too.

To take the building's measures and to create its 3D model, a three-dimensional remote sensing technique can be used. The aim is to do the surveying without acting on the building, within one day by a single person with simple and cheap equipment. The three main three-dimensional remote sensing techniques are building surveying, lasergrammetry and photogrammetry.

Jansa et al. (2004) compares lasergrammetry and photogrammetry techniques. Penard et al. (2005) explains that terrestrial remote sensing techniques are necessary to reconstruct the geometry of building façades as the resolution of aerial photogrammetry is not sufficient. Several research works are carried out on the automation of multi-images photogrammetry techniques (Mayer & Reznik 2007).

3.4.2 *Make the diagnosis of the existing building(s)*

The second function of the A1 diagram is "Make the diagnosis of the existing building(s)". It consists in calculating the performance indicators of the existing building(s), in particular the current energy consumption of the building(s). Besides all the information useful for the renovation must be gathered. For instance, the identification of access routes (roads, railways, waterways, etc.) is important to plan the transport of components to the building site.

Corgnati et al. (2008) proposes an operational rating procedure to assess the energy consumption of existing buildings. A "specific indicator of space heating energy consumption" based on metered energy consumption, is defined.

3.4.3 *Write the requirements of the renovation*

The third function of the A1 diagram is "Write the requirements of the renovation". It consists in

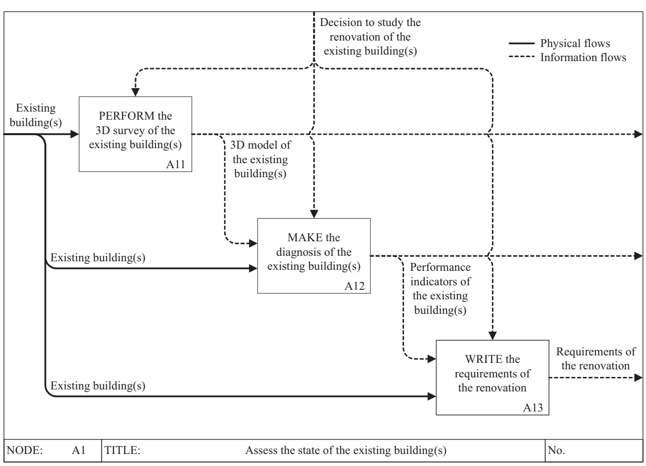

Figure 3. A1 diagram of the IDEF0 process modelling of industrialized thermal renovation with its three sub-functions.

defining the objectives of the renovation from the information on the existing building(s), in particular their performance indicators and possibly the identified constraints.

This process modelling of industrialized thermal renovation of apartment buildings is simple and will be refined. Nevertheless, it enables to identify the delicate points of each activity in the renovation process. Today there are industrial tools and methods to control the supply chain of the components and to implement them on the existing building(s). But to industrialize the whole renovation process, the activities of existing building assessment and study of the renovation should be also considered in detail as the success of the projects depends on them.

4 CONCLUSIONS AND PERSPECTIVES

The process modelling of industrialized thermal renovation of apartment buildings enabled to identify four functions: assess the state of the existing building(s), study the renovation of the existing building(s), manage the supply chain of the components and implement them on the existing building(s).

To pursue this research work, it is expected to visit some sites of artisanal renovation to identify the sources of non-quality, deadline/cost exceedance, etc. Then we will model the industrial renovation process with the Business Process Modelling Notation (BPMN) and we will consider in detail the different possibilities of logistic networks to optimally support this industrial renovation process. At the same time, the TBC Générateur d'Innovation company will develop the range of components required for the industrialized renovation with some of the building companies.

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Optimisation and simulation

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Using Ant Colony Optimisation for infrastructure maintenance Scheduling

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ABSTRACT: For the optimal planning of maintenance schedules for infrastructural buildings (bridges, tunnels, etc.) in urban road systems it is necessary to take not only the budget has to be considered but also the impact on traffic flow into account to avoid unnecessary traffic jams. In an ongoing research project we develop an optimisation tool for this multi-objective problem based on Ant Colony Optimisation.

In each iteration, the ants produce several different maintenance schedules for the maintenance over the next few years. Each of these schedules is formed by several scenarios of simultaneously closed roads. Parallel maintenance on different buildings can be modeled be introducing teams of ants. The scenarios are evaluated by an external traffic simulator. The quality of the different schedules, assessed by the waiting time created in the system, influences the amount of pheromone deposited on each schedule and accordingly the probability that this or a similar schedule is chosen by the ants in the next iteration step.

The building condition also has influence on the probability of choosing a certain schedule: buildings in bad condition are getting more attractive to be chosen—thus avoiding that only buildings in good condition and therefore with low repair costs are scheduled for maintenance while buildings in bad condition are left to further deterioration.

Additional constraints, e.g. budget constraints, can be introduced by applying a modification of the Elitist Ant strategy that guides the ants away from infeasible schedules.

1 INTRODUCTION

In a current research project we are developing a software tool to support the planning of maintenance measures for infrastructural buildings (bridges, tunnels, etc).

This planning is traditionally done by hand. The planner has to consider numerous constraints. Some constraints, as the steadying of the budget flow, which will reduce the administrative effort a great deal, can not be taken into consideration with this approach.

Also the impact on traffic flow by road closures due to maintenance work, whose minimization is a main optimisation goal, can only be considered in a very simplified way. It is not possible to evaluate the actual benefit of postponing the maintenance work at one site to avoid the simultaneous closure of two given roads.

The tool we are developing will search for a maintenance schedule to cover the next few years that fulfills all given constraints while at the same time keeping the impact on traffic as low as possible.

2 DEFINITION OF THE PROBLEM

The first goal of optimizing the maintenance schedule is to minimize the impact on traffic. This can be measured by the waiting time produced by the parallel closure of a set of roads.

In addition to this the schedule is subject to a number of constraints.

The most obvious and also the most important task is to schedule the maintenance work of one particular building before this building reaches a state where security is no longer guaranteed, i.e. the building is likely to collapse.

Apart from this security constraint, there are various other constraints set by the public and by monetary considerations.

For the public it is important to guarantee free-flowing traffic, in other words, not to block possible detours by setting up a parallel work zone. Also the blocking of arterial roads and urban freeways should be minimized by maintaining buildings on the same main road at the same time.

The monetary objective is to steady the budget flow over the years. Costs can also be reduced by adjusting the maintenance schedule to coincide with the maintenance work conducted by third parties who also use the building such as utility services and public transport organizations.

There are additional constraints that are known to the planner but are too complicated to be modeled in the planning software. So the planning tool should produce a set of solutions that satisfy the given constraints for the planner to choose from.

3 APPROACH

3.1 *Ant Colony Optimisation*

As there is no known algorithm for finding an exact solution for the described problem in reasonable time it has to be solved approximately, e.g. by metaheuristics. We use Ant Colony Optimisation (ACO) to construct the schedules, as ACO has performed very well with similar problems (e.g. Lee 2009).

ACO is a constructive metaheuristic developed by Dorigo (1992). It is based on the behavior of natural ants that are able to find the shortest route between their nest and a source of food by communicating via a chemical substance called pheromone. As they move ants deposit pheromone and prefer routes with greater deposits of pheromone. So, in time, this positive feedback guides the majority of ants along the same path (cf. Dorigo & Stützle 2004; Boysen).

The first problem on which ACO was applied was the Traveling Salesman Problem (TSP, Dorigo 1992). Since then ACO has been applied to many other problems, for instance, the bi-criteria TSP (García-Martínez et al. 2004), the Vehicle Routing Problem (Barán & Schaerer 2003; Reimann et al. 2004), the Quadratic Assignment Problem (Stützle & Dorigo 1999), Timetabling Problems (Socha et al. 2002), Construction Site Planning (Ning et al. 2010), and Scheduling Problems (Merkle et al. 2002; Solimanpur et al. 2005; Christodoulou 2010). For an overview see Dorigo & Stützle 2004.

The basic design of the algorithm is shown in Figure 1.

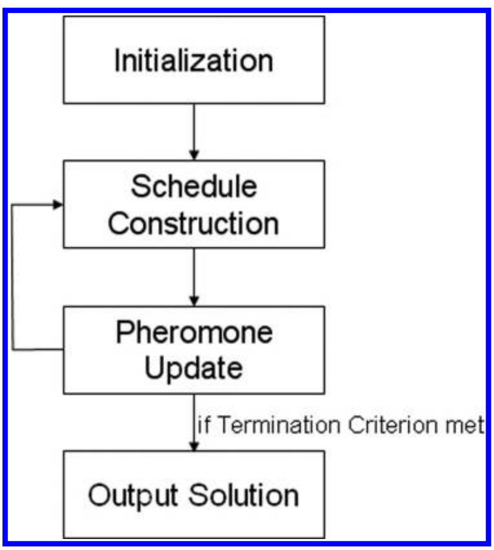

Figure 1. Algorithm.

3.2 *Objective function*

Our goal is to minimize the impact on traffic. This can be described by the waiting time produced by establishing a set of working zones that will lead to a closure of some roads.

The waiting time is measured by comparing the travel times in an undisturbed net at rush hour to the scenarios set by the maintenance schedule. For each schedule containing *n* years, *n* scenarios (each with a number of roads closed at the same time) have to be taken into consideration. As evaluation value we choose the highest waiting time caused in one of the *n* scenarios of an *n*-year schedule. Another possibility might be to minimize the sum of produced waiting time over all *n* years.

3.3 *Problem model*

To solve the maintenance scheduling problem by ACO we are structuring it as a graph (see Figure 2). To construct a schedule the ants move across the graph from left to right. The vertical columns in the graph represent the years. For each year the ants can choose from a number of buildings that have to be maintained, i.e. the rows of the graph.

To model the parallel maintenance of several buildings we are not using single ants, as in classical ACO, but ant teams as proposed by Lee (2009). Those ant teams are sets of ants that together construct a schedule. The choices made by the ants of one team are known by all ants of this team but not by the ants of the other teams. For example if building No. 1 has been selected by one ant in Team 1 in the first year, this building no longer has to be considered by the other ants in that team in year 1 nor by any of the ants from this team in the following years but it is still available for the ants in the other teams either in year 1 or, if not chosen then, in one of the subsequent years.

Following Dorigo & Stützle (2004) we create as many ant teams as there are buildings in our problem. This contributes towards a thorough exploration of the search space.

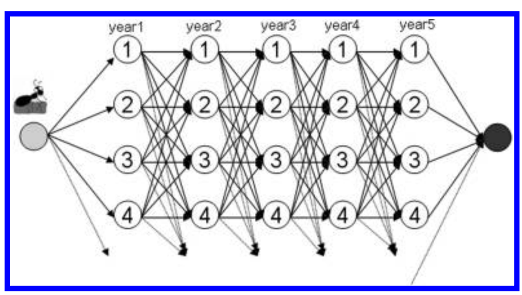

Figure 2. Problem structure.

3.4 *Initialization*

To ensure the algorithm performs well, the pheromone trails have to be initialized to a start value τ_0. This prevents the ants being influenced too much by the solutions found in the first iteration.

Dorigo & Stützle (2004) propose to set $\tau_0 = m/C^{nn}$ where m is the number of ants (or ant teams) and C^{nn} is the cost of a solution constructed at random or by any other heuristic.

3.5 *Construction of a schedule*

To construct a good schedule it does not matter in which order the buildings are maintained. Only the maintenance year of each building and the set of buildings chosen per year are of interest. So, contrary to traditional ACO, the pheromone is not deposited on the graph's arches but on the nodes.

An ant standing in column (i-1) chooses the next node j in the next column i with the probability

$$p_{ij} = \frac{\tau_{ij}^{\alpha} \cdot \eta_{ij}^{\beta}}{\sum_{l} \tau_{il}^{\alpha} \cdot \eta_{il}^{\beta}} \tag{1}$$

where τ_{ij} is the amount of pheromone on the node j in column i, η_{ij} is some heuristic information on this node and α and β are parameters for tuning the respective influence of pheromone and heuristic information.

In traditional ACO the heuristic information η_{ij} is obtained by estimating the benefit of the choice of the node j to the objective function. For example, in Traveling Salesman Problem, η_{ij} is usually chosen as the inverse of the costs of the arch i-j.

We can not estimate the effect of a choice on the objective function in our maintenance problem, as this is a highly complex function depending on all choices made for one year. In other words, closing just road A may not have a great impact on traffic flow but, if road A is the best detour for road B, the impact may increase enormously when maintenance is carried out both roads A and B at the same time.

We can, however, make use of η to steer the ants away from infeasible solutions: To describe the condition of a building, we use condition indices from 1 to 6 where 1 is the condition of a newly built building and 6 the condition of a building that is seriously at risk of collapsing (see also Schießl & Mayer 2006, 2007; Lukas et al. 2009). This condition index can be used to set η. Buildings with a high condition index should be more attractive for the ants than buildings in a good condition. Hence η and the amount of pheromone deposited at each iteration τ should be on the same scale. This serves to deter the ants from infeasible solutions in the first few iterations, with buildings reaching condition index 6 in the period under consideration and so violating the security constraints.

Alternatively one could set deadlines for the latest time for maintenance for all the buildings and construct η depending on the number of years until this deadline is reached.

A first implementation has shown that for different objectives for τ and η the weighting β should be very low to ensure convergence. Convergence here means that after a number of iterations the majority of ant teams will choose the same near-optimal schedule. Whereas Dorigo & Stützle (2004) propose $2 \le \beta \le 5$ for a TSP, in our implementation the algorithm shows best convergence—as well as best results in respect of the objective function—for $\beta = 1$. α should be set to 1 as in TSP.

The algorithm introduced here can either be applied to all buildings under one administration or only to buildings that have been selected beforehand because they are already in a bad condition. In the latter case, once a building has been chosen it no longer needs to be considered for the rest of the schedule construction; so it suffices for each ant team to have a memory where all buildings already in the schedule are stored. The buildings in this memory are not longer available for this ant team for the rest of the schedule.

In the case where all buildings are considered, it may be desirable to do maintenance work on the same building more than once during the period under consideration. In this case once maintained buildings still need to be available for choice but their condition index or their maintenance deadline, and accordingly their η, has been changed. However, this change in condition only applies to the one ant team that has scheduled the maintenance of the building. So a separate η-matrix has to be kept for each team, which changes during schedule construction and has to be reset after each iteration.

3.6 *Pheromone update*

After all ant teams have constructed full schedules, i.e. each ant of each team has chosen a building for each year of the period under consideration, the pheromone traces on the graph are updated.

First some pheromone evaporates on all nodes to enable the algorithm to forget bad solutions. This is done by decreasing the amount of pheromone by a factor ρ with $0 < \rho \le 1$. Following Dorigo & Stützle (2004) we choose $\rho = 0.5$.

After this, all ant teams deposit pheromone on all the nodes belonging to their respective schedules. The amount of pheromone $\Delta\tau_{ij}^{k}$ deposited by each team k is computed as the inverse square of the highest waiting time caused over the period under consideration in the respective schedule for each node *ij* that belongs to this schedule. It is 0 for all nodes that are not part of the schedule *k*. Also ant teams that produced infeasible solutions, for instance, solutions that violate the security or the budget constraints, are allowed to deposit pheromone to prevent premature convergence and to exploit the information contained in those solutions.

To avoid convergence to such infeasible solutions, we use the Elitist Ant (EA) approach (see also Dorigo & Stützle 2004). In the so-called elitist ant the best solution found so far is stored. As long as no better solution is found, this elitist ant in each iteration deposits pheromone even if its solution is not part of the set of solutions found in this iteration. The influence of this elitist ant can be weighted by a factor *e*. So the overall pheromone update is computed as follows:

$$\tau_{ij} = (1-\rho)\tau_{ij} + \sum_k \Delta\tau_{ij}^k + e\,\tau_{ij}^{EA} \qquad (2)$$

Dorigo & Stützle propose *e* to be the same as the number of nodes (buildings). As we have teams of ants, it is better to equate *e* to the number of ant teams.

EA was originally developed to guide the ants away from the greedy solutions, i.e. the solutions with to high influence on the heuristic information η, of the first few iterations. Since, in our approach η and τ describe different optimisation goals, the danger of such greedy solutions does not present itself. By not allowing infeasible solutions to become the solution of the elitist ant, the EA approach is a useful tool for getting rid of those solutions while still exploiting any useful information that may be contained in them.

3.7 *Next iteration and termination*

Following the pheromone update the next iteration step begins. The memories of the ant teams or the changes to the η-matrix are reset. The construction of the schedules is now aligned to the new values of the pheromone trails.

The algorithm terminates when over a given number of iterations the iteration-best solution does not change.

4 EXPERIMENTAL RESULTS

The algorithm described above has been implemented for a simplified model of the problem to test its performance.

On the one hand simplifications have been made in the deterioration function: the same deterioration function was set for each building, where the condition index is only dependent on the age of the building. Maintenance on a building resets its condition index to 1.

Nor have we coupled our model with a traffic simulator, so far. To model the impact on traffic flow, fictitious values of 'waiting time' caused by a work zone at the building in question were assigned to each building. The 'waiting time' per building was set to a value between 100,000 and 400,000 units. At simultaneous maintenance projects on some buildings their respective 'waiting time' values were summed up linearly. This, of course, is hardly realistic, but it works well as a simple surrogate model.

For the first test, only security and budget constraints were considered. Schedules not fulfilling those constraints were set as infeasible.

The test case concerned a set of 100 buildings with randomly assigned ages. 5 buildings can be maintained per year, so the worst possible schedule produces a maximum waiting time of 2,000,000 units. The period under consideration is 5 years. Without maintenance, 3 buildings reach condition index 6 (i.e. are likely to collapse) after the five years.

First tests have shown that the algorithm converges very fast—in about 20 iterations—to a feasible solution. The solutions found produce a maximum waiting time of 900,000 to 1,000,000 units. This is far better than a randomly constructed schedule that produces on average a maximum waiting time of 1,500,000 units.

5 CONCLUSIONS

Maintenance scheduling is an optimisation problem subject to many constraints. Using the algorithm shown in this paper it is possible to find near optimal solutions.

The algorithm is based on Ant Colony Optimisation. Modifications have been made to model parallel maintenance work and to guide the search in the first iteration step without knowing the benefit certain choices may have to the objective function.

A first implementation could show that the algorithm is capable of find good solutions.

A follow-up step will be to couple this model to a traffic simulator to obtain realistic values for the waiting time caused.

Future studies might improve on the performance of the algorithm by testing different settings of the ACO-parameters α, β and ρ. Further adaptations, should make the algorithm match the needs of building managers even better.

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Periodic operation of reverse osmosis desalination units

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ABSTRACT: The effect of changing the feed pressure to a tubular Reverse Osmosis (RO) process in pulse mode was investigated. The RO process was described by a dynamic rigorous model that was developed and validated in a previous work (Al-haj Ali et al. 2009). Two shapes of forcing feed pressure were studied: symmetric and asymmetric rectangular pulses. For both shapes of inputs, the results of periodic tests were compared with results obtained from the conventional static mode of operation. When symmetric pulse was implemented, it was found that increasing pressure wave amplitude leads to an increase in the permeate flow rate. Depending on the RO unit constraints, a maximum increase in permeate flow rate of around 5.5% could be obtained, which agrees well with the previous experimental results. For an asymmetric pressure pulse, unsteady state operation increased the permeate increased approximately by 3% compared to steady state operation. For both scenarios, the model attributed such enhancement in permeate flux to the decrease in salt concentration at membrane wall, which agrees with the widely accepted argument that relates such enhancement to the decrease in concentration polarization.

1 INTRODUCTION

Reverse Osmosis (RO) process is an important filtration process that is used extensively for the desalination of sea and brackish water all over the world. Concentration polarization and membrane fouling are major concerns in the successful operation of any membrane-based separation processes, since their net effect is to reduce the permeate flux and results in productivity loss. Fouling effects are characterized by an irreversible decrease in flux. Practically, fouling is eliminated by shutting the process down and cleaning the membrane by chemical or physical methods. Concentration polarization on the other hand results in reversible decline in water flux through the membrane. Generally, concentration polarization can be controlled using two main methods (Finnigan and Howell 1990): (i) changes in the characteristics of the membrane (Cornelissen et al. 2007), (ii) modification of flow rates and flow regime. The idea behind the second approach is to introduce instabilities in the flow of the module (Vrouwenvelder et al. 2006; Cornelissen et al. 2007). Examples of such methods include backwashing and periodic operation of the module, through forcing some of the process variables (Al-Bastaki and Abbas 1998). Periodic forcing improves the mixing of the solution on the feed side and, hence, reduces the build-up of solute ions near the membrane wall. The analysis of periodically forced reverse osmosis has received considerable attention in the literature (Kennedy et al. 1973; Finnigan and Howell 1990; Al-Bastaki and Abbas 1998; Al-Bastaki and Abbas 1999; Abbas and Al-Bastaki 2000; Abufayad 2003; Abbas 2007; Ramakul et al. 2009). One of the first works in this area was done by Kennedy and coworkers (1973) who varied the feed flow rate of a sucrose solution to a tubular RO process according to a harmonic function. The authors also correlated the experimental data using extended version of the theory of pulsed-flow reverse osmosis. Al-Bastaki and Abbas (1998) studied the periodic forcing of a small spiral-wound membrane through asymmetric square wave pressure pulses. The authors found that cyclic operation increases the permeate flux by approximately 6.5% over that obtained from steady-state operation. The increase in performance was justified by the reduction in concentration polarization in the process. Abbas (2000) investigated the periodic performance of a seawater desalination unit based on a small-scale commercial spiral-wound membrane.

Using a hollow fiber supported liquid membrane process, Ramakul and coworkers (2009) studied the effect of the periodic variation of feed flow rate on membrane performance. Compared to steady state operation, the authors reported an increase in the flux through the membrane with increasing both cycle amplitude and frequency. However, at very high frequencies, ~20 hr^{-1} in this work, the flux decreases because the liquid membrane is peeled out from the pores of hollow fiber.

Previous research work studied the unsteady operation of RO either experimentally or using simple process models. The main objective of this research is to investigate the performance of RO systems under periodic operation using a validated rigorous dynamic model.

2 PROCESS MODELLING

2.1 *Process description*

The process model describes a pilot-plant RO process. This process consists of a tubular membrane module which is fed by a plunger pump. This pump is connected to a 30-liter tank. Permeate and brine products are collected in separate tanks, where the concentrations of the products are measured. The set-up is equipped also with temperature and pressure sensors that are distributed throughout the set-up. Detailed set-up description is given in (Al-haj Ali et al. 2009).

2.2 *Model development*

The process model consists of dynamic and steady state material balances including flux and axial velocity expressions, an energy balance equation, and different algebraic equations such as the concentration of salt at the membrane wall.

Model assumptions and detailed model derivation can be found in (Al-haj Ali et al. 2009). In this section, the model is briefly presented. The membrane module is divided into n increments, and mass and energy balances are made for each segment.

The permeate flux ($J_{v,i}$) through the membrane at, increment i, is described by the three parameter nonlinear Spiegler-Kedem (SK) model:

$$J_{v,i} = L_p\left[(p_{b,i} - p_{p,i}) - (R_j')^2\,\nu R T c_{w,i}\right] \tag{1}$$

where $p_{b,i}$ and $p_{p,i}$ are brine-side and permeate-side pressures respectively, is the intrinsic salt rejection and R is the ideal gas constant. C_{wi} is the wall brine concentration at the i-th increment. It is calculated using the flowing equation:

$$c_{w,i} = c_{b,i} \cdot \frac{\exp\left(\dfrac{J_{v,i} \cdot Sc^{2/3}}{j \cdot u_i}\right)}{R_j' + (1 - R_j') \cdot xp\left(\dfrac{J_{v,i} \cdot Sc^{1/3}}{j \cdot u_i}\right)} \tag{2}$$

with Sc is Schmidt number and j_i is Chilton-Colburn factor. For turbulent flow in smooth circular tubes it is given by

$$j_i \cong 0.0395\, Re_i^{-1/4} \tag{3}$$

with Re_i being the local Reynolds number in i-th increment. The dynamics of salt concentration in the brine leaving increment i, are given by the following equation:

$$\frac{dc_{b,i}}{dt} = \left(\frac{u_i \cdot c_{b,i}}{\Delta x}\right) - \left(\frac{u_{i+1} \cdot c_{b,i+1}}{\Delta x}\right) - \left((1 - R_j') \cdot \frac{4 \cdot J_{v,i}}{d}\right) \tag{4}$$

here u_{i+1} is the velocity of brine leaving the i-th increment. It can be obtained from a volumetric balance about the i-th increment, and is given by

$$u_{i+1} = u_i - 4J_{v,i}\Delta x/d \tag{5}$$

with Δx and d being the increment length and tube diameter respectively.

The energy balance, for the i-th increment is used to calculate the pressure in the brine-side for different i-th increments. It can be proved that the pressure leaving the i-th increment can be calculated as follows:

$$\begin{aligned} p_{b,i+1} = {} & \left(\frac{u_i}{u_{i+1}}\right) \\ & \times\Bigg(p_{b,i} + 0.5 \cdot 10^{-7} \cdot \rho_{b,i} \cdot u_i^2 \\ & -2 \cdot 10^{-7} \cdot f_F \cdot u_i^2 \cdot \frac{\rho_{b,i}}{d}\Bigg) \\ & -\left(\frac{4 \cdot \Delta x \cdot J_{v,i}}{d \cdot u_{i+1}}\right) \cdot \left(p_{b,i} + 0.5 \cdot 10^{-7} \cdot \rho_{p,i} \cdot J_{vi}^2\right) \\ & -0.5 \cdot 10^{-7} \cdot \rho_{b,i} \cdot u_{i+1}^2 \end{aligned} \tag{6}$$

where ρ_{bi} and ρ_{pi} being the brine and permeate density respectively and f_F is Fanning friction factor, given by

$$f_F \cong 2 \cdot j \tag{7}$$

The permeate production rate is the summation of permeate produced in each increments, that is

$$q = \sum_{i=1}^{n} J_{vi} \cdot \pi \cdot d \cdot \Delta x \tag{8}$$

When the cyclic mode is used, the mass transfer coefficient, k_p, can be estimated using the following expression (Kennedy et al. 1973):

$$\frac{k_p}{k_s} = 0.5 \cdot \left|1 + \frac{u_p}{u_s}\right|^n + 0.5 \cdot \left|1 - \frac{u_p}{u_s}\right|^n \tag{9}$$

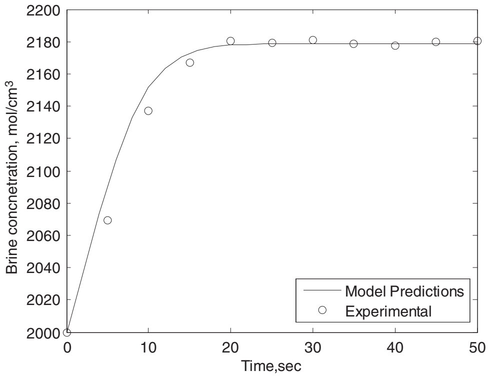

Figure 1. Model predication versus experimental data.

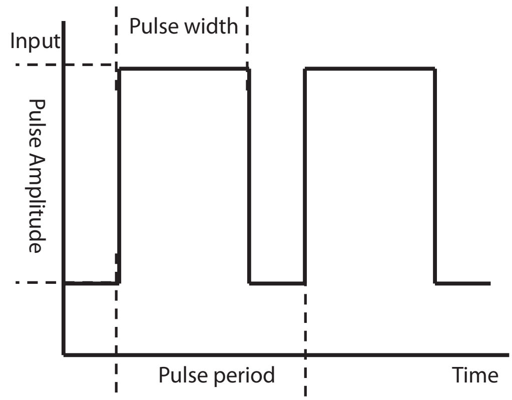

Figure 2. Schematic of an asymmetric pulse.

with k_s is the steady state mass transfer coefficient, us and up are the periodic operation and steady state velocities respectively.

The model was validated against an experimental lab scale RO unit. Figure 1 shows a comparison between brine concentration predicted by the developed model and the experimental data for a feed rate of 8.3×10^{-6} m^3/sec. As can be seen in this figure, the model predicts the experimental data very well. Detailed model validation can be found in (Al-haj Ali et al. 2009).

2.3 *Forcing variables*

There are two common variables that can be manipulated to force the RO process. (i) feed pressure (ii) feed flow rate. These variables were used in experimental studies in the literature (Kennedy et al. 1973; Al-Bastaki and Abbas 1998; Al-Bastaki and Abbas 1999; Abbas and Al-Bastaki 2000; Abbas 2007; Ramakul et al. 2009). Only the feed pressure is investigated in this paper. For cyclic operation, two shapes of forcing functions have been employed in published works, namely sinusoidal inputs and square wave variations (Douglas 1972). The latter approach, which is also known as the bang-bang type, has been shown to be better forcing function. Two shapes are considered: Symmetric shape, characterized by three parameters: pulse amplitude, pulse width and pulse period. But being symmetric the pulse width is always taken as half the pulse period. Therefore the forcing parameters to be investigated are the pulse amplitude and pulse period. The second shape to be investigated is the asymmetric pulse. This type of forcing variable is characterized by three parameters: forcing amplitude, pulse width and pulse period, see Figure 2.

3 RESULTS AND DESCUSSION

3.1 *Forcing the feed pressure with symmetric pulse*

Figure 3 shows the variations of the ratio of permeate to the steady state value ($q_s = 1.51 \times 10^{-6}$ m^3/sec) with the frequency *f*(cycles/min) at fixed amplitude of forcing of $A_m = 1000$ kPa. The steady state value of pressure is fixed at 3500 kPa. First it can be seen that the ratio of permeate flow rates is always greater than 1.0 indicating that there is an improvement in the performance as result of the cyclic operation. Second, the figure shows that the ratio of permeate flow rate increases monotonically with the frequency of pulsing. Starting from a value of 1.01 at a low frequency of 10 cycles/min, the ratio of permeate flux rates reaches the value of 1.05 for a frequency of 60 cycles/min. This represents a 5.2% improvement. These results agree well with the experimental findings shown in previous works. Al-Bastaki and Abbas (1998) reported an improvement in permeate production rate ranged from 0.3 to 13%. In another work, Al-Bastaki and Abbas (1999) found that the maximum improvement in permeate flow rate is around 6.5%. Ramakul et al. (2009) obtained increase in permeate flux ranged from 1 to 17%.

In the same figure the average ratio of wall concentration to bulk salt concentration (C_w/C_b) is plotted. The trend of this ratio is exactly the opposite to that of the ratio of permeate. This confirms that the effect of the pulsing is to decrease salt concentration near membrane surface (concentration polarization). When the ratio of flow rates is at its highest value of 1.05, the value of ratio of salt concentration is at its smallest value of almost unity. Decreasing the frequency increases the ratio of salt concentration that reaches a value of 1.66 at the frequency of 10 cycles/min. The two plots confirm

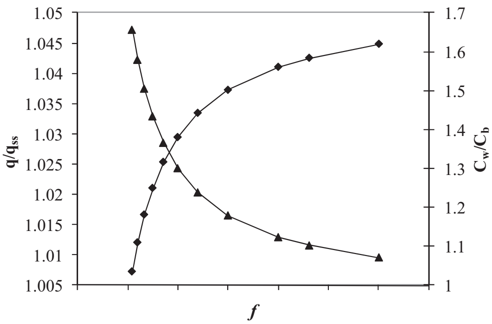

Figure 3. Effect of varying the frequency on the periodic operation of the RO unit. Square: ratio of permeate flow rates. Triangle: ratio of salt concentration. Forcing variable is feed pressure. Shape of pulse is symmetric. Forcing amplitude is 1000 kPa. Steady state pressure is 3500 kPa.

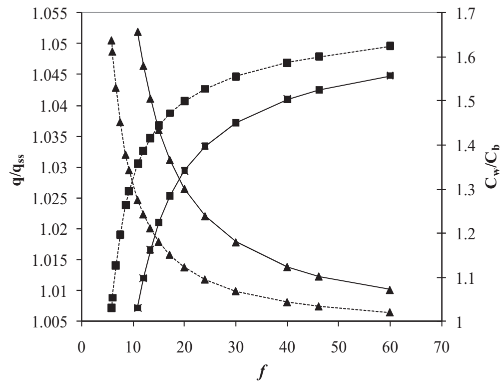

Figure 4. Effect of varying the forcing amplitude frequency on the periodic operation of the RO unit. Square: ratio of permeate flow rates. Triangle: ratio of salt concentration. Solid: Forcing amplitude is 1000 kPa. Dot: Forcing amplitude is 2000 kPa. Forcing variable is feed pressure. Shape of pulse is symmetric. Steady state pressure is 3500 kPa.

well the ability of the model to predict the effect of the forcing on the concentration polarization.

Next for the same forcing variable (feed pressure) and the symmetric shape, we examine the effect of changing the forcing amplitude (A_m). Figure 4 shows the results for A_m = 1000 kPa and A_m = 2000 kPa. It can be seen that an increase in the forcing amplitude increases the performance of the membrane, as the ratio of permeate flow rates is higher. At the same time, the concentration polarization decreases with the increase in the forcing amplitude. For the highest frequency (f = 60 cycles/min), the increase in the forcing amplitude from A_m = 1000 to A_m = 2000 kPa increases the ratio of permeate flow rate from 1.052 to 1.054. Obviously one cannot increase the forcing amplitude Am infinitely, since the upper values are dictated by the limits on the operating pressure of the unit. Also it can be noted that an increase of 100% in the forcing amplitude (from Am = 1000 kPa to Am = 2000 kPa) has resulted in limited increase in the performance. On the other hand for constant value of Am = 1000 kPa, the increase in the frequency of 100% from 20 cycles/min to 40 cycles/min has resulted in the increase of performance from 1.03 to 1.04. It is worth mentioning that model predictions are consistent with the experimental observations in (Al-Bastaki and Abbas 1998; Al-Bastaki and Abbas 1999). Note that limited enhancement is reported in this work because the capacity of the RO unit is limited and the effect of changing operating conditions on both permeate flow rate and brine concentration is restricted as described by Al-haj Ali et al. (2009).

Figure 5 shows the effect of operating at a higher steady state pressure of 5000 kPa at constant forcing amplitude of A_m = 1000 kPa. At this

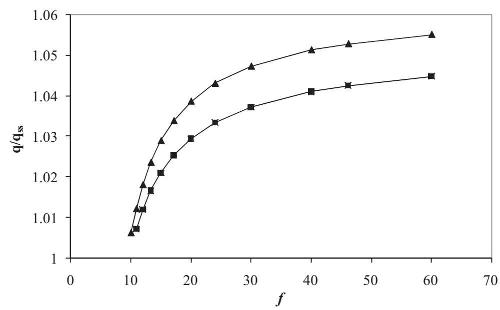

Figure 5. Effect of steady state pressure on the periodic operation of the RO unit. Square: steady state pressure is 3500 kPa. Triangle: steady state pressure is 5000 kPa. Forcing variable is feed pressure. Shape of pulse is symmetric.

new operating point, the steady state value of the permeate flow rate has changed to $q_{ss} = 2.19 \times 10^{-6}$ m^3/sec. Again, the permeate flow rate follows the well-known trend approaching the maximum possible permeation rate asymptotically with increasing frequency. The comparison between the ratio of permeate flow rates, shows that an increase in the steady state operating pressure increases the performance of the unit for a wide range of forcing frequencies. For example for the frequency value of 30 cycles/min, the increase of operating pressure from 3500 to 5000 kPa has increased the ratio of permeate flow rates from 1.037 to 1.047.

The effect of changing forcing amplitude on the performance of the unit is shown in Figure 6 for two values of periods: 2 and 4 seconds (corresponding

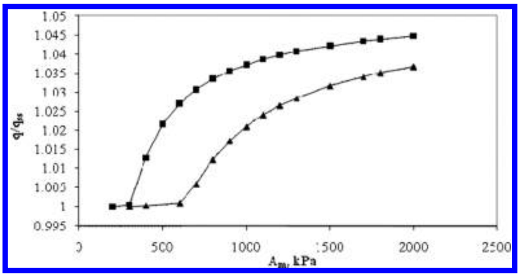

Figure 6. Effect of forcing amplitude on the periodic operation of the RO unit at different periods. Square: period 2 sec; Triangle: period 4 sec. Forcing variable is feed pressure. Shape of pulse is symmetric. Steady state pressure is 3500 kPa.

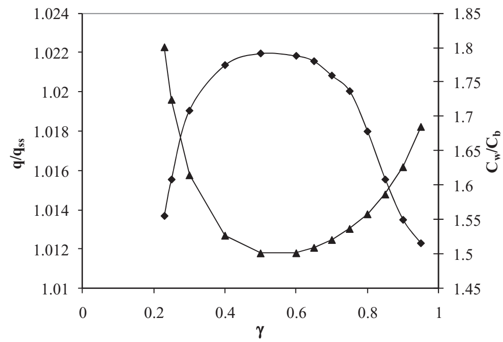

Figure 7. Effect of ratio of pulse width to period on periodic operation of the RO unit. Square: ratio of permeate flow rates; triangle: ratio of salt concentrations. Forcing variable is feed pressure. Shape of pulse is asymmetric. Steady state pressure is 3500 kPa. $f = 20$ cycles/min.

to 40 and 20 cycles/min). First it can be seen that the increase in the forcing amplitude increases monotonically the permeate flux. This is expected as the increase in the forcing amplitude amounts to increase in the average pressure and this would increase the unit performance. The effect of change in the period is shown in the same figure. It can be seen that an increase in the period from 2 to 4 seconds, leads to a decrease in the permeate flow rate. For example for a forcing amplitude of 1000 kPa, the increase of period from 2 to 4 leads to decrease in the ratio of permeate flux from 1.04 to 1.02 which corresponds to about 2% decrease. It worths to be noted that the trends in these figures are consistent with the experimental results reported in the literature (Al-Bastaki and Abbas 1998; Al-Bastaki and Abbas 1999; Abufayad 2003; Abbas 2007).

3.2 *Forcing the feed pressure with asymmetric pulse*

In this section, the results of forcing the feed pressure using an asymmetric pulse are reported. As it was mentioned in the previous section, the parameters of the forcing shape are the pressure lower and upper bounds in addition to the ratio of the pulse width to pulse period (γ). Figure 7 shows the effect of γ on the performance of the unit. The steady state operating pressure is still maintained at 3500 kPa. The figure shows that there is a clear maximum at about $\gamma = 0.5$, corresponding to a ratio of permeate flow rates of 1.02, thus an increase of around 2%. On the same figure are shown the variations of the ratio of average wall concentration to brine concentration. The plot shows an exactly opposite trend, where the concentration polarization reaches a minimum when the permeate flow rate is at its maximum value. This behavior is consistent with what has been reported in the literature (Al-Bastaki and Abbas 1998; Al-Bastaki and Abbas 1999; Abufayad 2003; Abbas 2007).

4 CONCLUSIONS

The performance of the cyclic operation of a reverse osmosis desalination unit was studied. The RO process was described using a dynamic rigorous model that was validated in a previous work. Two pulsing shapes were investigated: symmetric and asymmetric shapes. The symmetric cyclic variation of the feed pressure showed a continuous increase in the performance of the unit with increasing either the period or the forcing amplitude with a maximum increase in permeation rate of about 5%, which is consistent with previous experimental findings reported in the literature. This enhancement is attributed to the reduction in the effect of concentration polarization that was successfully predicted by the model. It was also found that the use of asymmetric operation improves the permeate flow rate for ratio of pulse width to period (γ) in the range of 0.2 to 1.0 with the optimum value occurred around $\gamma = 0.5$.

It should be noted that the developed model can be used to study both steady state and dynamic operations. This model can be extended to describe other tubular membrane systems by changing only few model parameters as number of tubes and membrane permeability. This model can be used also in formulating optimisation problem to optimize design and operating parameters in order to maximize the recovery ratio or the profitability of the system. Besides, this model can be used to develop practical control algorithms for RO desalination plants (Al-haj Ali et al. 2010).

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Logistic cargo loading optimisation

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ABSTRACT: The German railway company Deutsche Bahn will build a new and innovative terminal for intermodal transportation called Megahub. Since the technology, like the longitudinal conveyance system, has never been used before, the ICSCE was assigned to simulate the operation of the terminal. Main objectives are to verify the performance capability and to determine an optimal configuration in terms of expensive portal cranes needed. Therefore, an optimised transshipment of the cargo units has to be simulated. This includes a resource constrained optimisation problem. The paper will present a sophisticated greedy algorithm, which produces such good results, that a difficult heuristic optimisation can be disregarded.

1 INTRODUCTION

Nowadays, European cargo traffic is realised as *intermodal* transportation: A regular cargo unit travels the short parts at the beginning and the end of its journey by motor truck and the longest part of the journey by train or even by ship. This is the best practice in terms of costs and environmental aspects.

The stations, where a cargo unit is transshipped from a truck to a train, vice versa or from train to train, are called *terminals*. The transport between these terminals is accomplished by rail with a hub and spoke system: A train originating from a terminal carries cargo units for many destination terminals. The train moves—via a spoke—to a hub, where several trains meet. There, the cargo units are sorted according to their destinations.

In the past, the trains have always been sorted in marshalling yards, where the waggons, which carry the cargo units, are shunt. This is a time consuming procedure. Therefore, in modern terminals large portal cranes transship the cargo units directly from waggon to waggon. Such cargo traffic from one train to another is called *gateway traffic*.

Over the last years, the amount of transported cargo has risen significantly. This is one reason for the need of more terminals. Furthermore, the storage capacity of the seaports reaches its limits. The cargo must quickly be transported away from the ports and hence be sorted in the inland. Therefore, the German railway company Deutsche Bahn (DB) has decided to build new and very powerful terminals called *Megahubs*.

These Megahubs shall feature new technology and concepts that have never been used before. The lacking experience makes prior computer simulations of the workflow necessary. The ICSCE has been assigned to perform these simulations.

The primary objective of the simulations, which require a workflow optimisation, is the verification of the performance capability of the planned Megahubs. A suitable working configuration has to be found, stating for example the quantity of portal cranes needed to satisfy the demands with an aspired maximal workload of 80%.

Due to an enterprise agreement of confidentiality, not all the exact values and results can be published.

2 THE MEGAHUB TERMINAL

The first Megahub terminal will be built in Lehrte, close to Hanover. The area of Hanover is an important intersection for the North-South and East-West tracks and therefore predestined for a Megahub.

The terminal will cover 6 tracks, each with a length of 700 m (see Figure 1). The width of the terminal is approximately 80 m.

There is storage space on both sides of the tracks and a truck loading lane on one side. In the storage, most cargo units can be stored in several levels. Thus, the storing logic needs intelligence, but this topic is not covered in this article.

The terminal configuration could vary from 3 to 6 portal cranes, each spanning all tracks and the truck loading and storage lanes. Portal cranes can move longitudinally up to an adjacent crane or the end of the terminal.

In the region of the cranes, the trains must not have overhead contact lines. Thus, the 600 m long trains have to enter the terminal with speed and stop

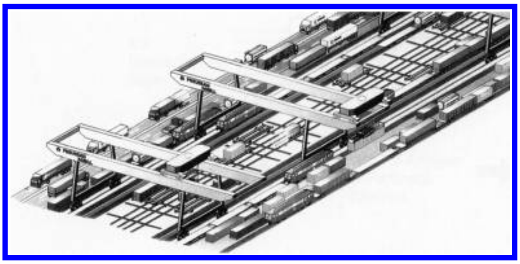

Figure 1. Planned Megahub terminal (from Franke 1998).

at the left or right end of the terminal, depending on their direction. Afterwards, the trains are static until they leave the terminal.

However, the specialty of the Megahub is the Longitudinal Conveyance System (LCS). Additional 3 tracks with 45 lateral connections forming a rectangular grid are located in the middle of the terminal. On this grid, plenty of self-propelled waggons operate, which can turn their wheels by 90 degrees. They are called *roll cars* and each of them is capable of carrying one cargo unit.

The LCS is a great improvement, because longitudinal transports can be very difficult for the cranes, which cannot pass each other. The optimal quantity of roll cars shall be a result of the simulation.

3 OPERATION REQUIREMENTS

The railway operator prescribes the demands that the terminal has to satisfy: 16 standardised trains must be handled in the defined period at night. This is the basic scenario; in the future it shall be more trains in the same time.

Each of the 16 trains has 30 waggons. A waggon carries 1.6 cargo units. This is an average value, because the cargo units have different sizes and different characteristics. The characteristics of a cargo unit can vary in type, weight and a hazardous material classification. Different cargo units mean that not every unit can be placed on every waggon.

The 16 trains enter and leave the Megahub on a prescribed schedule. 30% of the cargo units are already on the correct train. 4% are transshipped to and from trucks. There are further values that define how many cargo units are transshipped between which trains. The origins and destinations of all cargo units are defined in two matrices, one for incoming and one for outgoing traffic.

In order to produce first results, these matrices are generated randomly with regards to the given constraints. In the future, the matrices will be optimised and prescribed by the railway operator.

4 THE MODEL

In order to simulate the operation of the Megahub terminal, the transshipment of the cargo units has to be described. A time discrete model is used.

Every cargo unit has an origin and a destination. The units are lifted and moved by the cranes. The *load cycle* of a crane includes:

- the movement to the cargo unit,
- the lift of the unit,
- the movement to a destination, not necessarily to the final destination,
- the disposal of the unit.

The crane and the crab have maximum velocities and accelerations for their movement, as well as for the lift of the unit, and a creep speed while approaching another crane. With these values, the theoretical minimal times needed for the different steps can be calculated from the appropriate distances. The results are then increased by several additions in order to get realistic values: There are additions for the oscillation of the cargo unit during the lift, a security buffer and an addition called “human factor”.

Once the load cycles are implemented, the coordination of the cranes among each other is necessary. Not only collisions have to be avoided, but also the working areas have to be defined. There are two approaches to do so: *dynamic* or *fix* crane areas.

With dynamic crane areas, a crane can move all over the terminal while not colliding with other cranes. This gives a crane great flexibility but also the danger of handicapping other cranes. With fix crane areas, the terminal is divided among the cranes, which provides a calmer and well-arranged operation. The size of the areas can then be adapted to the workload of a crane. Furthermore, overlapping areas have to be defined. Their size has the same (dis)advantages as the dynamic crane areas.

If a single crane moves a cargo unit from its origin to its destination within one load cycle, the transshipment is called *direct*. Due to time and place constraints, *indirect* transhipments are also necessary. In these cases, the cargo unit is buffered in the storage or transported with the LCS or other cranes.

The Longitudinal Conveyance System (LCS) consists of 3 tracks with 45 lateral connections. The roll cars establish a kind of traffic circle: the middle track is only used for loading, unloading and parking. The upper track is used for traffic in one direction, the lower track for the opposite direction. The rail bound roll cars have defined velocities, accelerations and time additions for the turning of the wheel axle when changing directions. The same discrete movement model as for the cranes can be used, only the collision avoidance is more complicated: The roll cars have to obey more sophisticated traffic rules.

With this logic, the roll cars can execute their tasks and transport cargo units to their temporary destinations or close to them, if another roll car occupies the desired target spot. Furthermore, the roll cars can also be used as storage to buffer the units in order to avoid transportation time to the storage space.

Another important behaviour of roll cars is their movement while they do not carry a cargo unit. There are two possible approaches.

The first approach is to distribute the roll cars equally over the terminal in order to provide the best availability for cranes at any time. At certain times, for example when an empty roll car has to move out of the way for a loaded car, the empty car looks for the largest area without roll cars in the LCS and moves there.

In the second approach, a crane can order an empty roll car to the spot where it is needed. This requires though, that the simulation knows in advance, when a crane needs a roll car, because the cranes do not have the time to wait for roll cars.

The distribution of the tasks to the cranes and roll cars is performed on the basis of a priority queue. This logic is part of the optimisation problem and therefore treated in the following sections.

5 THE CONSTRAINT OPTIMISATION PROBLEM

With the model outlined in the section above, the Megahub terminal is ready to work; the cranes are ready to transport the cargo units. Every transport of a cargo unit is a task executed by a crane or a roll car. The only information the cranes need, is which crane executes which jobs in which order. A method is needed, which distributes all the jobs to the cranes in an optimised order that fulfils all the demands and the given constraints. This type of problem is called a resource constrained project scheduling problem (RCPSP), as described in Neumann (2003).

The primary resources in this case are the cranes. They are constrained by their capacity, which means, that they can only carry one cargo unit at a time, and thus execute one job at a time. The second constraint is in place: a crane must not collide with other cranes and must not leave the terminal. The model already fulfils these two constraints. The third—and for the optimisation most important—constraint is the time. Every job has an earliest beginning and a latest end: a cargo unit cannot be handled before it is in the terminal and must be on the correct train when the train leaves. Trains do not wait for cargo units.

The RCPSP to schedule the jobs in an optimal order that fulfils the constraints mentioned above is a difficult challenge. The point though, that makes the challenge even harder and different from other scheduling problems, is the possibility to segment a transport: A cargo unit can be temporarily buffered or transported with the LCS. These options expand the quantity of possible solutions by far.

Furthermore, the operation of the LCS itself can be optimised to use the roll cars most efficiently. In a first approach, the LCS will be optimised separated from the crane jobs. In the future, a coupling of the optimisations can be useful.

In order to start the optimisation and compare the results of different simulations, an objective function has to be defined. The primary objective is the quantity of cargo units that did not reach their destination train in time. With regards to the constraints, the quantity should be 0, but that is not always possible. The secondary optimisation objective is the minimisation of the longitudinal movements of the cranes as they correlate with costs. In order to improve the objective function, three additional criteria can be derived from these first two: A crane standing still is negative just like the segmentation of a transport in general, because it costs time. Furthermore, a crane moving without a cargo unit is negative. That costs time and money.

In conclusion, the summarised objective is to schedule the jobs in time and place as close together as possible. Figure 2 shows the longitudinal movement of 4 cranes over the time.

In an illustrative way, the optimisation is comparable to the game Tetris: The single transport jobs have to be moved around and squeezed into gaps (within the constraints) to maximise the density.

The solution of the resource constrained optimisation problem is described in the next section.

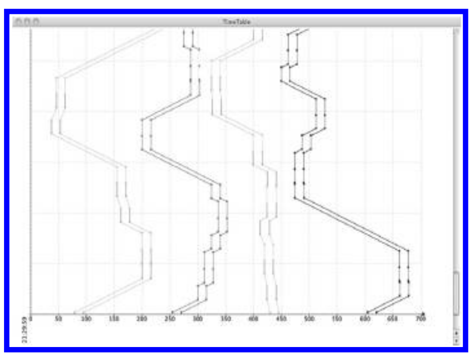

Figure 2. Longitudinal movement of 4 cranes over the time.

6 SOLUTION

Like most order optimisation problems, the present problem is NP-complete. It cannot be solved by exhaustive enumeration, because the solution space is too large. Heuristic methods have to be applied. A possible solution is the use of Genetic Algorithms: Valid orders of all crane jobs are coded as individuals with repair and penalty functions enforcing the constraints.

A greedy algorithm was developed in order to deliver a good start value for the heuristic optimisation. Surprisingly, this algorithm produces such good results, that a subsequent optimisation has not been necessary so far.

The character of a greedy algorithm is the short-sightedness: It picks the best choice for the current state without looking any further at the proceeding process, as described in Hofmann (2008).

The developed algorithm determines the most important cargo unit to transport in every discrete time step. For this purpose, all cargo units are arranged in a priority queue. The priority of a cargo unit is composed of several values, with each value corresponding to a part of the objective function:

The primary objective is that a cargo unit is transported in time. Thereto, the unit has to be loaded off the incoming train and onto the outbound train before the trains leave the terminal. Each of these trains has its priority p_t defined by the exponential function 1:

$$p_t = \frac{1 - e^{2 * \frac{current\_operating\_time}{\max\_operating\_time}}}{1 - e^2} * 100 \quad (1)$$

The *current operating time* is the time that a train is already in the terminal. The max *operating time* is the time between entering and leaving the terminal. The exponential function raises the importance of the units on a train steadily and climbs extremely high shortly before the train leaves. The priority of a train, which is not in the terminal, is zero.

The basic priority $p_{u,0}$ of a cargo unit is calculated with function 2, in which $p_{t,s}$ is the priority of the source and $p_{t,d}$ of the destination train:

$$p_{u,0} = \max(p_{t,s}, p_{t,d}) + 0.5 * \min(p_{t,s}, p_{t,d}) \quad (2)$$

In cases, when units are already unloaded off the source train or have the storage as destination, there is only one train significant and the other one is set to zero.

Furthermore, there are several additions to the basic priority. The most important one is the addition for reserved spots: If a cargo unit is in the location, in which another unit has to move, the priority of the latter unit is added to the priority of the first one. This prevents originally unimportant units from blocking important ones. A second addition is applied to units on roll cars. This fixed value ensures that the roll cars are unloaded quickly and available for new tasks. The summation of the basic priority $p_{u,0}$, these and some other additions results in the improved priority $p_{u,a}$ of a unit.

Finally, the distance d from the crane to the cargo unit has to influence the priority in order to minimise empty and longitudinal crane movements. If the distance d is smaller than a defined maximum influence range $d_{\max}$, the final priority is calculated with function 3:

$$p_{u,f} = \frac{d_{\max}}{d} * p_{u,a} \quad (3)$$

Having the priorities for all cargo units defined, a vacant crane will chose the top unit. If the direct transshipment is possible, the crane will execute it. Unfortunately, there are at least two common reasons that make the direct transport impossible. It is possible that the destination train for a cargo unit has not arrived at the Megahub terminal yet. In these cases, the unit is transported to the closest vacant storage location and loaded onto the destination train later. Mutual blocking of cranes a second reason for indirect transshipment: the crane cannot reach the desired destination of the unit. This is the application area of the Longitudinal Conveyance System (LCS). The crane transports the unit to the closest vacant roll car, and the car moves to a spot nearby the destination.

These many small steps to improve the greedy algorithm accumulate to a good solution.

7 SIMULATION AND RESULTS

In order to simulate the operation of the Megahub terminal, the model was implemented with the programming language Java. Since the matrices for incoming and outgoing traffic are generated almost randomly, many simulations—in most cases 100—were executed for each terminal configuration. The simulation runs in discrete time steps and can be easily controlled by the visualisation (Figure 3).

The first result of the simulation is the unexpected success of the greedy algorithm, which was originally designed to produce a good start value. In the test cases, the algorithm always fulfilled the primary objectives and constraints. Only with the secondary optimisation objectives, it was not quite as good as the costly calculated optimal solution, but achieved values around 90%. In exchange, the great advantage of the algorithm is its speed. In the practical application, the speed is almost as important as the result. Thus, the implementation of a heuristic optimisation is not urgent, since the relation between the quality of the result and the calculation time of the greedy algorithm cannot be improved by a heuristic optimisation.

The primary results for the Deutsche Bahn are the workloads of the cranes for the different terminal configurations. The cranes shall satisfy the demands with a desired maximal workload of 80%. Therefore, it was necessary to define evaluation intervals. Unfortunately, the cranes always are always engaged in our model: The workload is 100% most of the time (see Figure 4).

To overcome this problem, the cranes were slowed down. Thereto, it is an option simply to decrease the velocities of the cranes, but it is more realistic to add rest periods at certain critical points. Since the average duration of a load cycle is another interesting result, this value can be used to simulate a workload of 80%.

With this modification, it was possible to calculate the desired results like an optimal quantity of portal cranes and roll cars. Furthermore, all kinds of sophisticated charts for different workloads were generated. Exemplary results of these evaluations are values for the extensive utilisation of the LCS as storage facility or the quantity of cargo units transported by the LCS in a certain period. Figure 5 shows the relative frequency of LCS-transported units in a 20 minute interval.

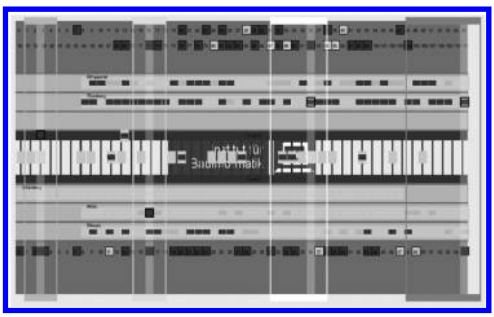

Figure 3. Visualisation of the simulation tool.

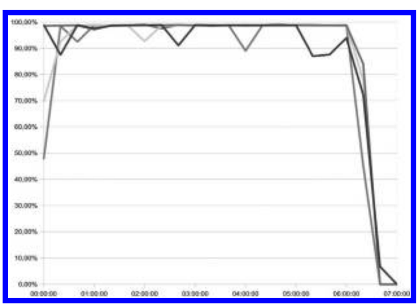

Figure 4. Workload of four cranes over the defined period.

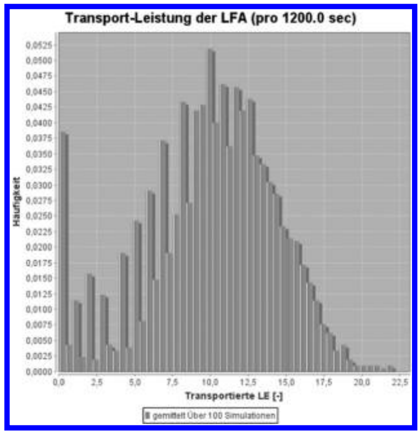

Figure 5. Relative frequency of LCS-transports in 20 minutes.

8 SUMMARY AND PERSPECTIVES

This paper has presented the operation simulation of the prospective Megahub terminal. To achieve the simulation, a discrete model has been developed. The model describes the movements of the portal cranes and the roll cars in the longitudinal conveyance system. The necessary optimised distribution of the transport tasks is a resource constrained scheduling problem. It is solved with a sophisticated greedy algorithm, which produces surprisingly good results. Thus, a heuristic optimisation is not necessary for the practical application. The main objectives of this work have been reached: The desired performance capability of the Megahub could be verified and an optimal system configuration has been determined.

One of the next steps in the future is the simulation of malfunctions and delays in the operation. Thereto, operation times could be stochastic. Furthermore, a fast heuristic optimisation will be attempted with Genetic Algorithms as mentioned in section 6. The optimisation of the LCS can be coupled to it.

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Graph-based approaches for simulating pedestrian dynamics in building models

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ABSTRACT: This paper presents different path-finding algorithms for simulating pedestrian dynamics in building models. Starting from a given model (scenario), we show how to automatically derive a visibility graph. This graph is used as the underlying structure for routing pedestrians from their sources to their destinations. Based on this graph, we search for fastest routes by means of a conventional Dijkstra algorithm where we assign dynamically changing travel times as edge weights. To update the shortest paths due to changing edge weights, we introduce a heuristic A* algorithm, which is faster in finding optimal paths. We compare the results of our approach to a variant where we assign Euclidean distances as static edge weights. Additionally, we show that the A* algorithm has a better performance in finding the shortest path for most cases.

1 INTRODUCTION

Pedestrian simulations are used for a wide variety of applications, namely the identification of possible conflict points or bottlenecks in buildings and surroundings, the determination of evacuation times, the determination of optimal evacuation routes etc. To simulate pedestrian behavior, a wide variety of different models is used as summarized in [Schadschneider et al. 2009]. Our objective is to describe individual movement and navigation processes in buildings with a microscopic graph-based model.

2 MODEL DESCRIPTION

To simulate pedestrian movements, we use two different model approaches. The first approach combines a cellular automaton [Burstedde et al. 2001, Emmerich and Rank 1997, Kinkeldey 2003, Klüpfel 2003, Kretz 2007] and a force model according to [Schadschneider et al. 2009]. The second approach [Helbing et al. 2001, Höcker et al. 2009] describes pedestrian movement by means of space continuous interactions. The individual interaction force contains a driving term directed to a destination as well as a repulsive term originating from other pedestrians and obstacles.

One challenge of this model is the calibration between the different force terms to achieve the most realistic walking and navigation behavior in complex buildings. To solve this challenge, we configure the individual driving force by introducing a visibility graph [de Berg et al. 2000] of the scenario topography. This graph is used to navigate pedestrians from their sources to their destinations by applying different routing criterions and algorithms.

3 GRAPH DERIVATION FROM THE SCENARIO TOPOGRAPHY

To map pedestrian movements within a scenario, we introduce a method to construct a visibility graph as the underlying structure for routing algorithms. We automatically derive the graph from the scenario topography consisting of sources and destinations as well as different kinds of obstacles such as walls, polygons (e.g. desks inside buildings) etc. From this initial geometry we start extracting the graph by applying the following two steps.

First, we place so-called orientation points on the bisector of each convex obstacle corner (refer to Fig. 1 top). We choose the distance to the corners according to an appropriate measure such that "artificial" congestions at corners can be avoided

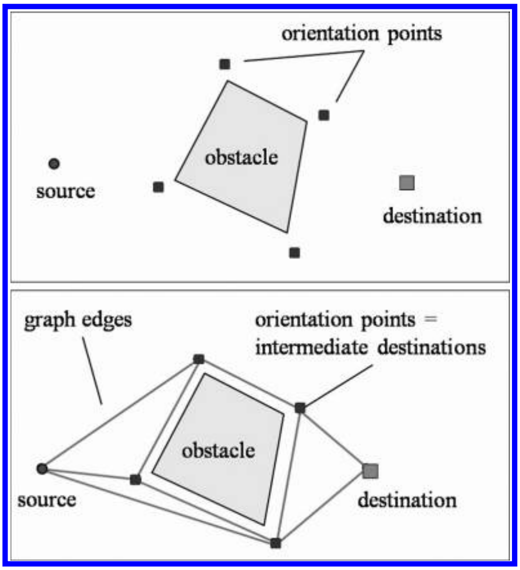

Figure 1. Graph derivation from the scenario topography.

when pedestrians are trying to pass these orientation points.

In order to prevent that a point is not visible from the related corner, it has to be checked if another obstacle, e.g. the line of a wall, intersects the imaginary sight line between the corner and the point. In case of an intersection, we move this point closer to the corner.

In detail, the orientation point is placed midway of the shortest distance vector between the cutting edge and the corner (see Fig. 2).

To avoid orientation points that are too close to each other, we prune these redundant points by melting these neighboring points into one new point as shown in Figure 3.

Finally, the resulting orientation points represent the graph nodes.

Second, we start connecting these graph nodes with each other subsequently. Two orientation points are connected by means of a graph edge, if they are in sight of each other. In addition, they are connected to sources and destinations in the same manner.

After the graph generation we perform a check for dispensable edges to achieve a most efficient navigation process. For individual routing, there are only edges necessary leading around the obstacle corners. This characteristic can be detected with a so-called corner related sight criterion illustrated in Figure 4. The obstacle corner is connected to a sight crossing area bounded by the imaginary sight lines placed along the two corner sides.

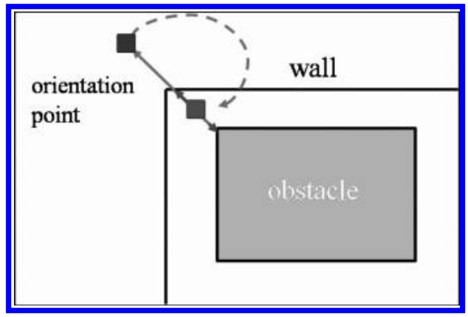

Figure 2. Repositioning of orientation points.

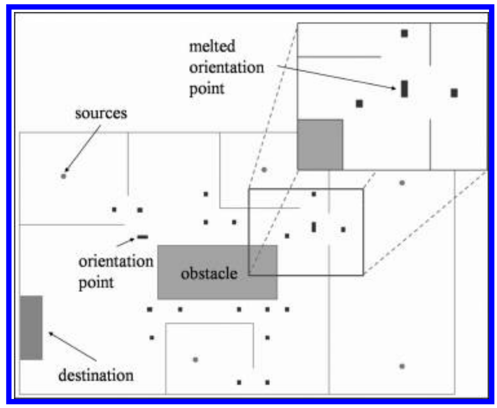

Figure 3. Melting of two adjacent orientation points.

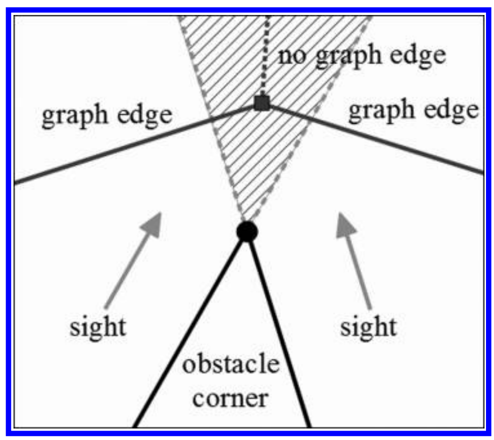

Figure 4. Graph edge reduction.

We define an edge as necessary if it leads from the orientation point out of the sight crossing area. If this criterion is not fulfilled, the edge will be disconnected. In this manner, up to 75 percent of the initial edges can be reduced.

The resulting graph (as shown in Fig. 1 bottom) can be used for the routing algorithms defining at least one path between the sources and destinations if it exists. This follows directly from the construction procedure.

4 ROUTING ALGORITHMS

We apply different algorithms, which are based on the developed visibility graph, to route the pedestrians from their sources to their destinations.

More precisely, we combined two different routing strategies: The first one is a common shortest path finding algorithm [Dijkstra 1959] with dynamic edge weight variation. The second one is a heuristic algorithm according to [Russel and Norvig 2003], which is able to find as well an optimal shortest path, but in most cases more efficiently—depending on the heuristic values. We start with the description of the common Dijkstra algorithm with adaptation to our problem, followed by the A* algorithm with the heuristics we used.

4.1 *Dijkstra algorithm with dynamic edge weights*

Since the Dijkstra algorithm considers edge weights to compare two edges while traversing the graph from a given node (source) to a designated node (destination), we focus on determining the edge weights to match pedestrian behavior.

Our approach is to take travel times as edge weights instead of Euclidean distances. The travel time is derived as follows: For each edge, we define an area associated with it (see Fig. 5). Then, we count the number of pedestrians that are traversing along that edge. From the number of pedestrians in relation to the whole accessible size of the area, we derive the density factor as in (1):

$$density\_factor = \frac{number\_of\_pedestrians}{accessible\_edge\_area} \quad (1)$$

As edge areas can overlap, we have to associate pedestrians not only to one edge area but to all surrounding edges whose areas are affected.

According to [Weidmann 1993], there exists a relation between density and velocity for pedestrians (see Fig. 6). We take this proposed relation to obtain a deceleration factor for the pedestrians.

More precisely, we take the density factor of an area and derive the corresponding velocity. Multiplying this velocity with the Euclidean distance of the edge, the expected travel time is computed as:

$$travel\_time_{edge} = veloc_{edge}^{density} * dist_{edge} \quad (2)$$

As travel times may vary over time depending on the density on each edge, we have to re-compute it with each pedestrian that enters a specific edge area.

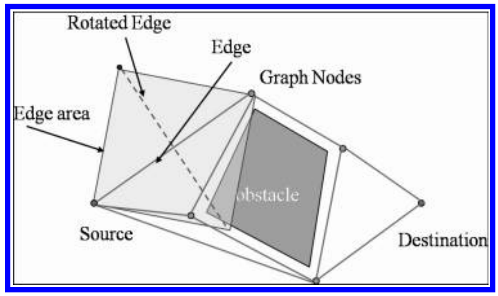

Figure 5. Construction of an area to measure density on an edge: The edge is rotated by 90° to define the corner points of the area.

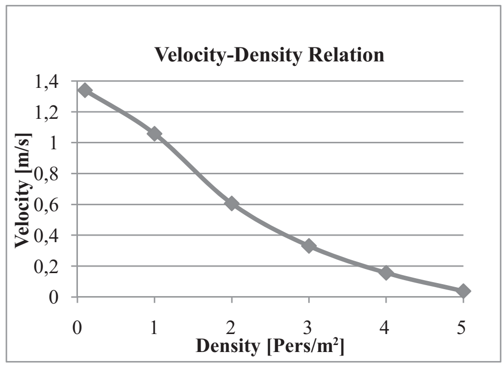

Figure 6. Velocity-Density Relation for pedestrians, as proposed in [Weidmann 1993].

Consequently, a shortest path is time-dependent, so that pedestrians entering the scenario later may get assigned a different path than earlier ones.

In case of more than one route leading to the target, this technique even allows us to avoid congestions by dynamically performing checks for each pedestrian entering an edge. If this assigned edge has a density factor that exceeds a certain threshold, we search for a different route.

4.2 *A* algorithm with heuristic node weights*

To minimize runtime for the re-computation of shortest ways, we introduce the A* algorithm, which may not need to inspect each graph edge (like a conventional Dijkstra algorithm) by applying an additional heuristic.

The A* algorithm uses therefore edge weights as well as node weights calculated with a node related function $F(x) = G(x) + a \cdot H(x)$. $G(x)$ represents the real length of a detected shortest path between a source and the (intermediate) destination x. The real length equals the sum of the path edge weights, e.g. the Euclidian distance or the travel time. $H(x)$ represents the approximated length of the path between

x and the destination, scaled with a factor a. For $a = 0$, the A* algorithm analyzes all graph nodes—like the Dijkstra algorithm. For $a \neq 0$, the heuristic path search ranges over a part of the network only, so that the time involved gets reduced.

A pseudo code of the A* algorithm is illustrated in Figure. 7. The algorithm uses a list L_O for analyzed graph nodes and a closed list L_C. At the beginning of an individual routing process, both lists are empty. L_O is initialized with the source and weights it with $F(x)$. Next, we loop until the destination is reached or if L_O does not contain a graph node any more.

The loop starts with checking L_O and removing the element x with the lowest node weight. For this element x all successors x_N will be analyzed, which are not already contained in the closed list L_C.

Successors which are not even contained in the list L_O, are added to it and weighted with $F(x)$; furthermore, a backward-reference between each successor x_N and x will be stored.

If a successor x_N is already contained in L_O, the node weight and the backward-reference of the successor x_N will be updated, if the calculated weight is lower than the stored node weight.

At the end of each loop, the element x will be stored in the closed list L_C.

In case of removing the destination from L_O for examination, the algorithm terminates and

Algorithm: Path-finding
Parameters: Graph $G{:=}(X;E)$, source s in X, destination d in X, node weight function $F(x)$

init node lists L_O und L_C
store s with $F(s)$ in L_O
while L_O is not empty
  select node $x \mid x$ in L_O, stored $F(x)$ = min
  remove x from L_O
  if $x == d$
    init path P from s to d using the stored backward-links
    Result: P
  end if
  for all successors x_N of x in G
    if x_N not element of L_C
      if x_N element of L_O
        if $F(x_N)$ < stored $F(x_N)$
          stored $F(x_N) = F(x_N)$
          set the stored backward-link from x_N to x
        end if
      else
        store x_N with $F(x_N)$ in L_O
        store backward-link from x_N to x
      end if
    end if
  end for
  store x in L_C
end while
Result: No path between s and d found

Figure 7. Pseudo code of the A* algorithm.

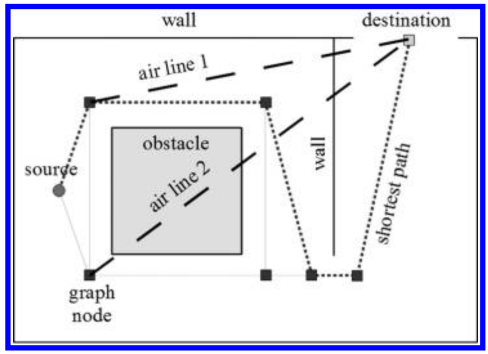

Figure 8. Heuristic path search with the air line distance.

reconstructs the shortest path between the source and the destination via the stored backward-links.

A commonly used definition of the heuristic function $H(x)$ is the Euclidian distance of the air line between the current graph node and the destination. The air line distance heuristic describes individual map knowledge about the surrounding space and the related navigation behavior realistically.

Figure 8 illustrates such a heuristic path search with a simple scenario. The approximated shortest path is depicted by a dashed line leading from the source (left in the figure) to the destination (right in the figure). It runs permanently along the lowest air line distances. In this manner, it differs partly from the real shortest path, which runs along the lower side of the obstacle. In this case, the heuristic term $H(x)$ dominates the node weight function $F(x)$.

5 APPLICATION EXAMPLE

By means of the presented model approaches and routing algorithms, pedestrian flow inside an office building was simulated.

Figure 9 illustrates the scenario topography of our example scenario. On this scenario we first ran the conventional Dijkstra algorithm with static and dynamic edge weights and compared the results. Additionally we applied the A* algorithm on this scenario and show that the number of visited nodes can be sufficiently smaller than with a conventional Dijkstra algorithm.

5.1 *Comparison of the Dijkstra algorithm with static and dynamic edge weights*

For the comparison between static and dynamic path finding, we used the first, space discrete model approach, as described in [Klein et al. 2010]. Pedestrians are placed inside the offices (dots); their destination is situated outside the building.

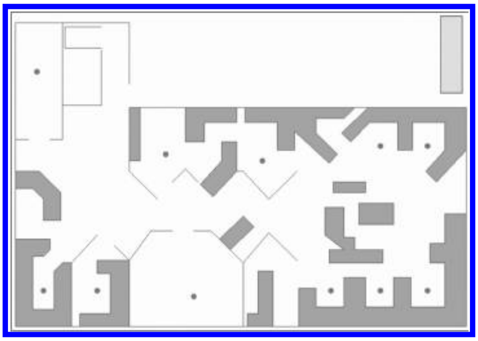

Figure 9. Topography of the tested scenario: The grey areas and lines define obstacles and walls of the building, the dots refer to sources, and the rectangle on the upper right corner defines the destination of all pedestrians.

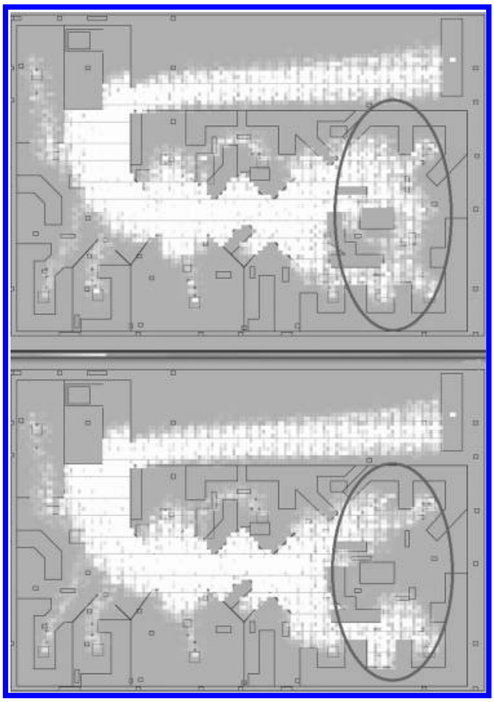

Figure 10. Mainstream of pedestrians shown for the static path algorithm (left) and dynamic path algorithm (right).

In order to observe density effects, we generated pedestrians periodically (six pedestrians per source and second) until a sufficient number (750 pedestrians) was reached.

Figure 10 shows the mainstream (the counted number of pedestrians that passed on a rectangular grid cell throughout the simulation)—in the upper picture for the static shortest path where we assigned the Euclidean distance as edge weights and in the lower picture for the dynamic fastest path.

Applying the static path algorithm, we can observe that all pedestrians walk the same route as there is no dynamical adaptation of new routes. In contrast, the mainstream resulting from the dynamic path algorithm shows that there were pedestrians who changed their route according to the densities on the conventional shortest path. We get a better distribution of the pedestrians throughout the right part of the office.

The drawback concerning runtime is—that in the dynamic version—a new fastest path has to be calculated as soon as an edge exceeds a certain density.

5.2 *Results for the A* algorithm*

To resolve these runtime issues we can calculate these individual dynamic paths—depending on the travel time—more efficiently by using the heuristic A* algorithm instead of the conventional Dijkstra algorithm. The behavior of the A* algorithm was tested with the simulation tool JWalkerS [JWalkerS 2010], which is an object-oriented implementation of the second, space-continuous model approach (see section 2).

Figure 11 illustrates a visibility graph calculated with JWalkerS: Orientation nodes are represented by small-sized circles. The simulation is restricted to the routing process of a single pedestrian from an office room towards the exit which is located in the upper part of the figure. The pedestrian is depicted by an elliptical space in the lower left room of the office building. The approximated shortest path is located between the heuristically analyzed graph nodes represented by black filled quadrangles. It is clearly visible that the path search ranges only over a small part of the network whereas the conventional Dijkstra algorithm visits every single node of the graph. As a consequence, the performance of the A* algorithm is much better than the one of the Dijkstra algorithm for this specific case.

More generally spoken, one can observe, that in buildings with a complex geometry (e.g. many

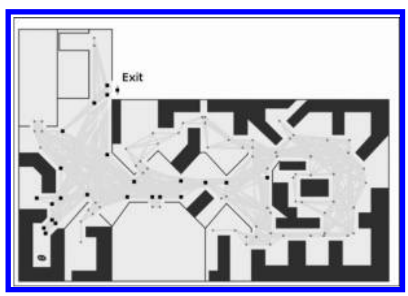

Figure 11. Searched graph nodes (black filled quadrangles) of an individual routing process with the A* algorithm ($a = 1$). A conventional Dijkstra algorithm would have visited all nodes of the visibility graph.

offices or rooms), the A* algorithm does not search within rooms that are neither positioned in the same direction as the air line to the destination nor close to the real shortest path.

Configuring the A* algorithm, it must be considered that the probability for differences between approximated and real shortest path increases with the heuristic factor. From our experience we can state, that for $a \leq 1$, we could not observe any differences between the real shortest path and the one found by the A* algorithm.

6 OUTLOOK

In this contribution, we introduced new methods for a graph-based description of paths in buildings as well as individual routing processes.

Here, the paths are automatically derived from scenario topography by placing orientation points on the bisectors of convex obstacle corners and calculating sight connections. By using criterions for melting adjacent orientation points and for reducing sight connections on crossings, we developed an efficient graph structure by reducing the number of nodes and edges as far as possible.

Moreover, we presented routing algorithms which can dynamically assign new individual paths depending on pedestrian densities. Along with an application example we demonstrated that this dynamic assignment leads to a more realistic prognosis of pedestrian route choice and thus of pedestrian distribution. To minimize the path-finding time involved, we introduced an A* algorithm using the airline distance between an orientation point and a destination as heuristic value. The A* algorithm is able to the individual paths faster than the conventional Dijkstra algorithm, for specific cases as we described in Section 5.2.

Nevertheless, there are still some aspects of the graph structure as well as the routing algorithms to be investigated.

In order to simulate multi-level scenarios, graph-based models for level connections like stairs or escalators must be taken into account. For a multi-level navigation process, a further stage of the air line heuristic is necessary, e.g. with a temporary orientation to the level connections. Besides, another heuristic representing individual route decision criterions must be developed.

To be more efficient in deriving the edge weights, we will improve the algorithm in defining non-overlapping edge areas. Another step will be to implement a detection of pedestrian cluster which can be associated with the corresponding edges.

To reduce runtime and start re-calculation of fastest path only when necessary, further work has to focus on defining precise criteria, e.g. slow down factors on edges or distance ratios of k-shortest paths etc.

Given this dynamical path-assignment, a next step will be to dynamically vary a scenario during runtime (with occurring events like door closure or fire).

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Black box vertical applications—useable numerical simulation tools for engineering analysis

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ABSTRACT: In this paper we consider the lack of penetration of simulation tools in many industries. The author suggests that the issue is mainly due to the design of the software tools themselves and the lack of tailoring of the computational methods in those software embodiments. In particular, the solid modelling and mesh generation steps in Finite Element Analysis form a work flow issue, with the complexity, expertise and time resource necessary for that step usually being one of the main reasons why simulation is avoided.

Herein the author presents a more effective approach to simulation software design—*Black Box Vertical Applications*. In particular, a manifestation of this software design approach is presented in the form of well test analysis software for the petroleum industry. This software embodies the crucial solid modelling and mesh generation stages in a tailored workflow that results in a fast and easy to use numerical simulation tool for well test engineers with little or no knowledge of numerical simulation techniques. The key to the utility of the software is the embodiment of expert knowledge by filtering the techniques required for the particular analysis problem for which it is meant and limiting the functionality of the software to that application uniquely.

1 INTRODUCTION

The last thirty to forty years has seen many orders of magnitudes of increase in computing power, from the punch card era and computers that filled entire rooms, right through to 2 GHz laptops, with 2–3 Gb of memory. During that period, the increased computing power has facilitated the development of computer-based tools for engineering. In particular, the advent, in the last ten years, of windows type interfaces has seen the development of software, such as information management systems, that use the combined computing and visualisation (data representation) power of PCs, and new approaches in analysis, particularly in numerical simulation. We have now reached a stage where simulation problems, hitherto unthinkably large to compute on a standard desktop PC, are well within the scope of a PC that would cost less than €1000.

This means that we can now rethink our attitude to numerical simulation, its potential uses and cost effectiveness. No longer do we have to consider such analyses as beyond the scope of everyday design, as too complex, requiring specialists, expensive hardware and endless data preparation. This is the dawn of the era of *black box vertical applications*—software that encapsulates the specialist knowledge needed for advanced simulation of engineering problems in a form that is easy to use, tailored for the specific area of application and which yields results quickly and in a format that is meaningful to the analyst.

2 NUMERICAL SIMULATION

The mathematical formulation of many phenomena in engineering leads to its expression in the form of a partial differential equation. An engineer may want to solve such equations in order to determine the pore pressure at a point under a structure, calculate the maximum temperature in a mechanical part or determine the electrical potential at some key point in an electrical component. In order to solve the equation, the engineer has two possible approaches available to him/her (a) find a closed form/analytical solution (b) use some numerical solution technique, such as the finite element method of analysis (Zienkiewicz & Taylor, 1991). Finding a closed form solution requires complex mathematics and such solutions have inherent limitations in that the geometry and material properties have to be simplified. (Carslaw & Jaeger, 1959) Depending on the situation, such simplifications could render the results of little use. In contrast, the alternative numerical approach facilitates the simulation of:

- arbitrary geometries,
- complex material distributions,
- material & geometric non-linearity.

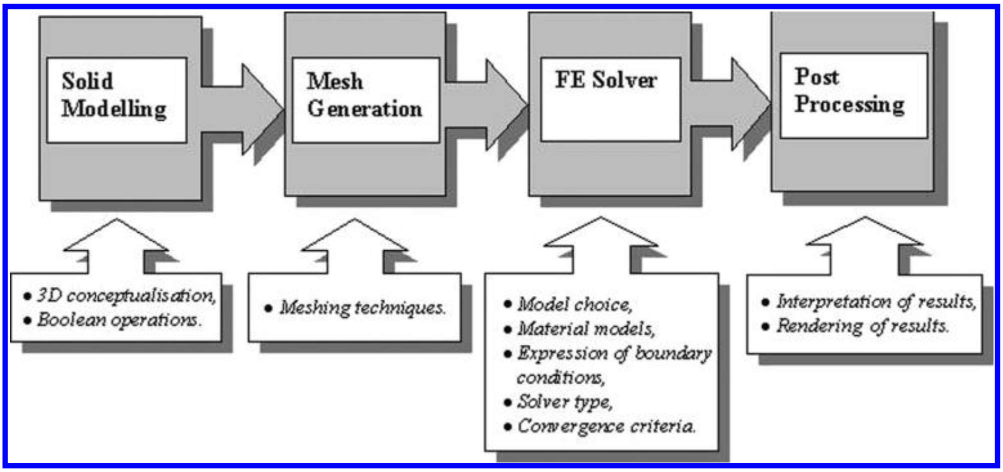

Figure 1. The major components of finite element modelling software.

However, despite these advantages, it is generally perceived as too expensive in terms of employee training and the time necessary for model building and simulation. It is this author's contention that, whereas this negative attitude to numerical simulation may have been somewhat justifiable before, this is no longer the case.

The main steps involved in solving such partial differential equations (as generally result in the mathematical modelling of engineering phenomena) using the *finite element method* are indicated in Figure 1. This numerical approach generally results in the problem being formulated as a set of simultaneous equations. For geometries and material layouts that reflect real cases, these equations can be as many as tens of thousands (although certain models, such as fluid flow in aerodynamics, can yield millions of equations). The solution of such vast sets (tens of thousands) of equations is no longer in the realms of specialist computers, nor is it in the sole domain big laboratories and universities, but can be run in a matter of minutes (or seconds) on modern day desktop PCs. However, having the computing power to solve the equations sets that occur in numerical simulation is only one part of the puzzle. In fact, in many ways the interface of the software and the work involved in creating the model for analysis is more important to the practical use.

Because these key steps are common to most applications of numerical simulation, such software has been traditionally written to model many types of phenomena (from structural analysis to electrical potential). The resulting software, though powerful, generally needs a level of skill an expertise in the software itself, as well as the underlying numerical techniques involved in each step.

3 BLACK BOX VERTICAL APPLICATIONS (BBVA)

Some of the companies that produce general finite element analysis packages have woken up to the shortcomings of that approach (software learning curve, need for expert knowledge) and are realising that their users want tailored software, where superfluous functionality has been removed. ANSYS™ has allowed the tailoring of their package for specific applications for the last number of years through the use of scripting languages. More recently they have launched a new product, AI* Workbench, which is even more powerful in this regard. Such scripted applications are termed *vertical applications*—applications that are specifically tailored to the requirements of the engineer and for the solution of a single class of problem. A simple example might be an application to perform a vibration analysis of a structural member or an application to analyse the resonance characteristics of a biomedical sensor.

3.1 *Parametric description*

The key to a vertical application is the *solid modelling* phase (Shapiro, 2001). The shape of any three-dimensional object can be viewed as being the combination of other simpler three-dimensional shapes (such as cuboids, spheres, cones and cylinders). When using a general-purpose solid modeller, the user needs expertise and experience to construct a model of his object using abstract Boolean operations. However, when dealing with a single class of models, it is feasible to build one or more basic shapes that envelopes all the possible shapes that will conceivably be presented by the user (or deliberately restricting the range of application to a useful subset of the overall possibilities).

These basic shapes (templates) must be defined by key dimensions referred to as parameters. This *parametric* description means that the user can then build a particular model by choosing a suitable template and adjusting the parameter values. Thus, the need for any expertise in solid modelling is eliminated.

3.2 *Black box*

When dealing with modelling problems where the range of the material properties, overall dimension and geometry is known *a priori*, it is possible to consider the development of an application that, not alone is tailored for the problem at hand in terms of pre and post processing, but requires no knowledge of the underlying solution technique on behalf of the user (the *FE Solver* stage in Figure 1). This approach would put the problem specific expertise of the user to the forefront, while placing the numerical simulation expertise in the background For example, an engineer designing a medical device such as a vascular stent would understand the design context (material behaviour, design constraints etc.) but would need numerical simulation to determine the fatigue life of the proposed design. A BBVA would bring the power of numerical simulation in an easy to use form to all engineers likely to require solutions to that class of problems, without the need for expertise in the underlying numerical modelling techniques.

3.3 *Example BBVA—PanMesh™: Tailored numerical well test analysis*

The process of well test analysis in petroleum engineering is quite complex and a full description is beyond the scope of this article. In brief, the process requires the well test engineer to model the pressure regime in complex reservoirs and compare model results to in situ measurements in order to better understand the makeup of the reservoir. The solution of the pertinent governing partial differential equation is used to produce a plot of pressure versus time at the well face (called a *type curve*) for the model. The well test engineer then plots the recorded (real) in situ pressure changes and compares them to the type curve produced from the model. There then follows a series of iterative steps whereby the engineer alters the model (geometry and material distribution, mainly rock permeabilities) so that the model *type curve* approaches the recorded (real) curve. When the curves match (closely) the engineer can assume that the model is a reasonable representation of the real reservoir.

3.3.1 *Speaking the user's language*

The most important aspect of any BBVA is that the entire application speaks the same language as the user (and not the conventional model, where the user is required to learn the language of the software). In this context, *speaking the language* means more than terminology. It implies that every aspect of the software, from model definition to post processing should be described in terms that are both meaningful and practical for the user. The application should fit into the user's conventional workflow, so that its use requires minimum investment on behalf of the user (and his employers). PanMesh™ has been developed with this important concept to the forefront of its design. All of its features and menus use terminology specific to the well test process. It simply fits into the workflow of its parent application PanSystem™ (a software application for standard well test analysis). Instead of choosing a conventional analytical solution scheme, the user can choose an *advanced simulation* option, whereby he/she is brought through the simple steps necessary to define a reservoir.

3.3.2 *Solid model & mesh generation for a reservoir*

PanMesh™ incorporates a patented solid modelling/mesh generation system that allows the user to generate meshes for relatively complex reservoir layouts. This process is made relatively easy due to the conceptualisation of the reservoir as being made up of polygons in plan and planar layers in elevation (see Figure 2). The GUI that has been developed to embody is flexible, easy to use and completely tailored for this purpose (to the extent that it does not at all resemble a conventional solid modelling environment—See Figure 3). The software also incorporates a *template* paradigm, whereby known geological formations (e.g. *channel sands*)

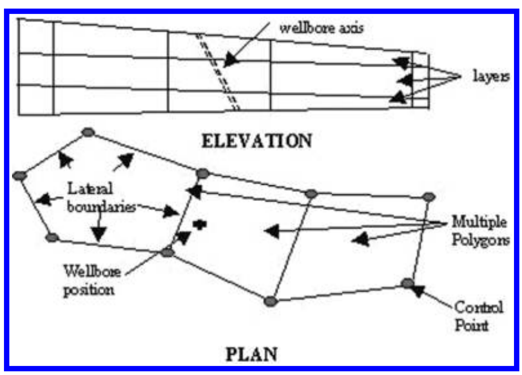

Figure 2. In PanMesh™, the generic solid model of a petroleum reservoir is conceptualised as a combination of polygons and layers.

that may be complicated to set up can be included as predefined combinations of polygons and layers (thus a *parametric description*) whose *control points* etc. can be moved to correspond to the layout of the current model. This allows the user to quickly and easily define reservoir models that are closer to reality and far beyond any conventional models for which there are analytical solutions.

The expertise necessary to transform the solid model into a valid finite element mesh and, in turn, to use that mesh to form a set of finite element equations and solve them is embodied in PanMesh™ and requires no additional input from the user (see Figure 4).

3.3.3 *Tailored post processing*

In PanMesh™, the solver step requires a simple click of a button as soon as the user is satisfied that the 3D rendered image of the model corresponds to the geological layout desired. The software produces a standard format well test *response curve* (see Figure 5) automatically as the simulation is

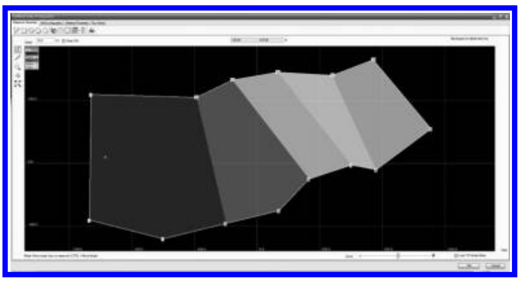

Figure 3. The solid modelling interface in PanMesh™ does not resemble a conventional solid modelling environment, but is tailored to this specific application.

running and, on termination of the simulation, it is immediately available to be analysed using standard well test analysis techniques.

The full 3D numerical simulation of a petroleum reservoir yields, not alone, the standard response curve (defining pressure drawdown at the well face) but also the entire pressure response at all points in the reservoir for each time station simulated. This results in a significant amount of data. To help the well test engineer process this output quickly and easily, specific functionalities have been added to PanMesh™ that help interpret the results.

Such features are not possible when solving the governing equation using analytical techniques and, whereas with more general-purpose finite element packages it would be possible to replicate certain of these functions, the significant difference with a BBVA such as PanMesh™ is that it is written specifically and solely for this application and, thus post processing, is completely bespoke. Therefore specifically tailored data probes such as colour contouring, an iso-surface to follow the pressure transient (depicting the *radius of investigation*), cut planes and flow planes are written into the software and available at the click of a button. Such tools facilitate quick and easy investigation of the simulation and give the engineer simple and efficient tools to determine the factors that contribute to the nature of the response curve (presence of fault planes, permeability contrasts, aquifers etc.). For example, a button has been included to allow the user to visualise the flow convergence at the tip of a completed well (see Figure 6) and tables showing percentage flows into separate completes or production from separate layers are also generated automatically (see Figure 7).

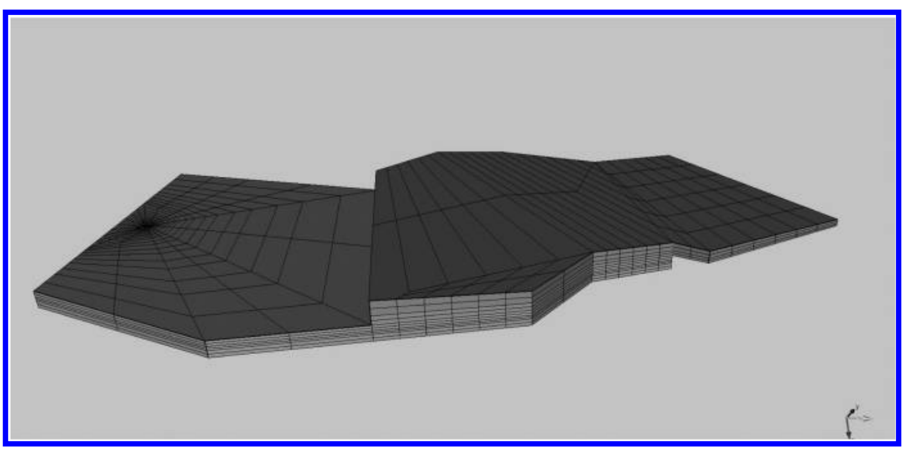

Figure 4. PanMesh™ automatically creates the finite element mesh required for analysis directly from the solid model.

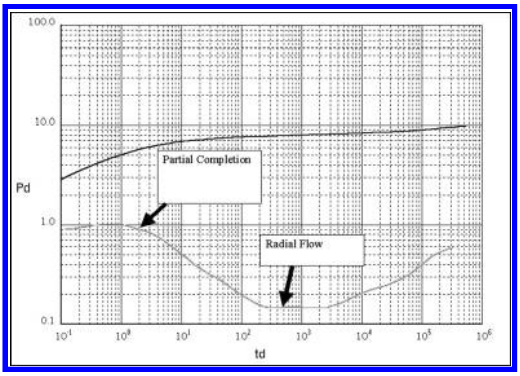

Figure 5. The software output is tailored to produce the standard style response curve that the well test engineer expects.

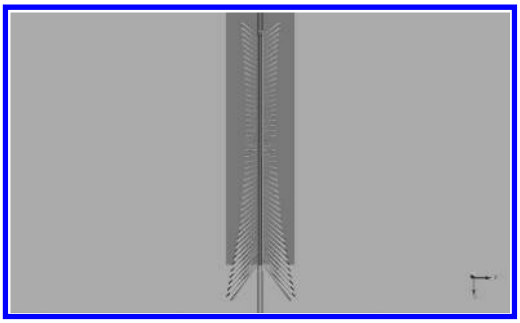

Figure 6. The user can generate visualisation of flow convergence at the click of a button.

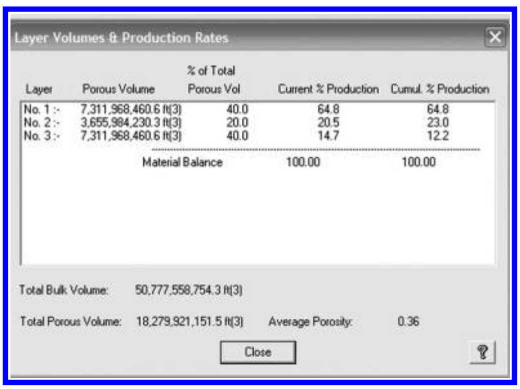

Figure 7. A BBVA can produce very detailed application specific results automatically.

4 FUTURE DEVELOPMENT

It is this author's contention that, in the future, *black box vertical applications* will be ubiquitous in engineering, replacing at one end of the spectrum, much of the simplified analysis that is still performed today and at the other end, the large, general purpose numerical simulation software (that requires a high level of expertise). The potential of such tools to improve designs is immense. Some areas that Kepler Engineering Software Ltd. is looking at are applications in:

- Shape optimisation for vascular stent design,
- Building Services—CFD analysis.

What is central to the utility of such tools is that they are developed in conjunction with experts in the area of application and that they are fully integrated into the workflow of the user.

5 CONCLUSION

The *BBVA* paradigm presented herein is a powerful method of bringing advanced analysis techniques to a wider audience. The practical implementation of the approach in a commercial product for the petroleum industry demonstrates that it is possible to create applications for specific areas whereby the intended user has no expertise in the underlying solution technique. The uptake of such tools will depend very much on the perceived benefit to each industry. The inherent increased accuracy of numerical simulation is not a goal in itself. However, where an accurate analysis means:

- A more efficient design.
- A safer design.
- A design that is cheaper to produce.
- An overall faster design process.

Then industry can justify the use of the technology and it will become the industry standard.

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Application of fuzzy analysis in simulation of construction processes

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ABSTRACT: Construction processes of the building industry are characterized by a large number of uncertain data and information. To increase planning reliability it is necessary to simulate at least critical construction stages in advance. For this purpose it is essential to model uncertain data and information in an adequate way to avoid unrealistic simulation results. Aleatoric uncertainty exists because of random variability, so methods of stochastics can be used. In case of epistemic uncertainty or rather fuzziness, however, it is impossible to describe information exactly; as there is no complete knowledge. For modelling epistemic uncertainty fuzzy set theory is applicable. In this paper an application of fuzzy analysis is presented, whereby fuzzy input variables are mapped onto fuzzy output variables. This represents an optimisation problem which can be solved with the aid of α-level optimisation. The method is illustrated by an example implemented prototypically in the simulation program AnyLogic®.

1 INTRODUCTION

Construction processes of the building industry are characterized by a large number of uncertain data and information, since every building process is unique. Reasons for this are external influences like the weather or the conditions at the building site and its surrounding area, but also the unique building itself, the construction methods and the construction equipment. No deterministic values for instance about the costs or the duration of processes are available beforehand.

This uncertainty can occur in aleatoric as well as in epistemic form (Helton & Burmaster 1996). Aleatoric uncertainty means random variability. To deal with it, methods of stochastics can be used. Hence variable data and information are modelled as random numbers whose distribution functions are estimated.

In case of epistemic uncertainty or rather fuzziness, however, it is impossible to describe information exactly; as there is no complete knowledge. For modelling epistemic uncertainty fuzzy set theory is applicable.

To increase planning reliability it is necessary to simulate at least critical construction stages in advance. To obtain realistic results uncertain input values have to be considered within the simulation (Möller & Reuter 2007). Although both forms of uncertainty have to be considered only fuzziness is regarded in this paper.

Objective of the current research is to develop a platform for the execution of construction projects, which amongst others allows visual simulations based on current operational data at all levels of abstraction (Mefisto 2009). Thereby the simulation model is based on a process model (see Fig. 1), which consists of several process modules. A process module describes a sub-process and obtains its data from different models, like the cost model, the building model or the scheduling. To obtain realistic results these basic models have to be enhanced, inter alia, by epistemic uncertainty.

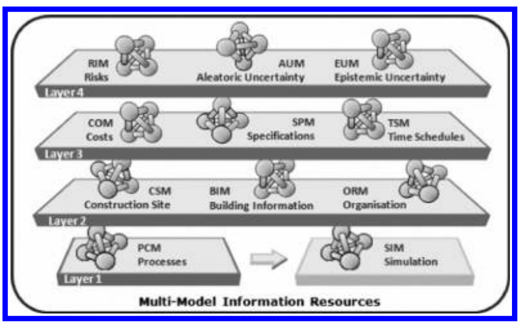


Figure 1. Process-centric multi-model space.

That is, beside deterministic values fuzzy values have to be regarded within these models too.

In particular, in this paper fuzzy analysis by means of α-level optimisation is presented. The method is illustrated by an example implemented prototypically in the simulation program AnyLogic®.

2 MODELLING OF EPISTEMIC UNCERTAINTY

Fuzzy set theory is a generalization of the binary Boolean set theory (Zimmermann 1992). Amongst others it takes into account that linguistic information is often not formulated precisely (e.g. low, medium, high temperature). Furthermore it is not always possible to get deterministic information because something is not exactly foreseeable (e.g. "delivery in about one week") or measurable. Figure 2 gives an example of a time series whose values cannot be determined exactly but only given in vague terms. They are not bounded exactly but fuzzy.

According to the fuzzy theory elements can belong to a set only with a certain degree–in contrast to the Boolean set theory, which only enables elements either to be or not to be a member of a set. The degree of membership is defined by the membership function $\mu_{\tilde{x}}(x)$ and hence a fuzzy variable $\tilde{x}$ is defined by:

$$\tilde{x} = \{x, \mu_{\tilde{x}}(x) \mid x \in \mathbf{X}\}, \qquad (1)$$

with X as the fundamental set.

If the membership function $\mu_{\tilde{x}}(x)$ is normalized, it is defined as:

$$0 \le \mu_{\tilde{x}}(x) \le 1 \quad \forall x \in \mathbb{R} \qquad (2)$$

$$\exists x_l, x_r \quad \text{with} \quad \mu_{\tilde{x}}(x) = 1 \quad \forall x \in [x_l, x_r]. \qquad (3)$$

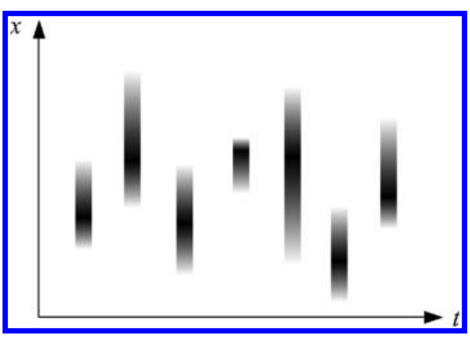


Figure 2. Uncertain time series.

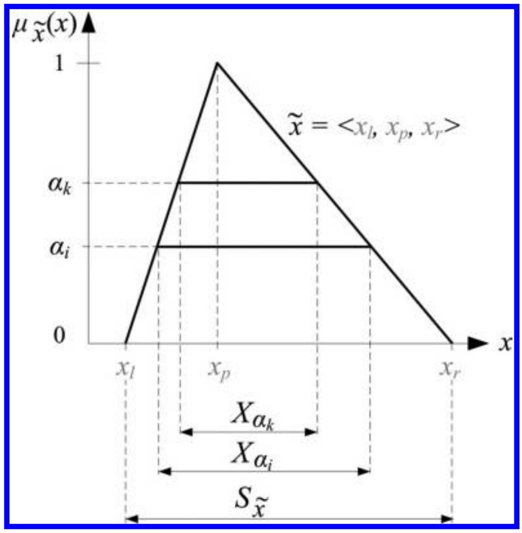


Figure 3. Convex and normalized triangular fuzzy number $\tilde{x}$ with its support $S_{\tilde{x}}$ and two α-level sets X_{α_i} and X_{α_k}.

Membership functions can occur in convex as well as in non-convex shapes. In the first case, the membership function monotonically decreases on each side of the maximum value (see Fig. 3). It is common to choose simple membership functions, for example in form of triangles or trapeziums.

Convex membership functions are presupposed in the following; applications of non-convex fuzzy variables are, for example, dealt with in (Reuter 2008).

A fuzzy variable $\tilde{x}$ is referred to as a fuzzy number if its membership function $\mu_{\tilde{x}}(x)$ is convex, piecewise continuous and if $\mu_{\tilde{x}}(x) = 1$ is fulfilled for only one precise value of x.

Epistemic uncertainty is a result of subjective–for example expert knowledge–and objective factors. In case of subjective data and information a general rule for defining membership functions does not exist. (Möller & Beer 2004) and (Viertl 2008) propose several possibilities depending on the available information. An objective factor occurs if measurements of interfaces between two complementary states yield grey tones which can be characterized by a continuous, monotonic increasing function. By the derivation of this function and its standardization the membership function is received (Reuter 2008).

3 FUZZY ANALYSIS

Fuzzy analysis is a method which enables to handle uncertain terms in form of fuzzy variables. For this purpose, fuzzy input variables $\tilde{x}_n$ are mapped onto fuzzy output variables $\tilde{z}_p$. This represents a mapping problem which can be solved by means of the extension principle. Under the constraint of convex fuzzy input variables α-level optimisation according to (Möller & Beer 2004) is numerically more efficient. For this, α-level sets of the fuzzy variables are used.

3.1 α-*level sets*

A fuzzy variable $\tilde{x}$ can be divided into any number of α-level sets X_{α_i} (see Fig. 3) for real numbers $\alpha_i \in (0, 1)$, where

$$X_{\alpha i} = \{x \in \mathbb{R} \mid \mu_{\tilde{x}}(x) \geq \alpha_i\}. \tag{4}$$

In case of convex fuzzy variables each α-level set X_{α_i} is a closed interval $[x_{\alpha_i l}, x_{\alpha_i r}]$ with

$$x_{\alpha_i l} = \min[x \in \mathbb{R} \mid \mu_{\tilde{x}}(x) \geq \alpha_i] \quad \text{and} \tag{5}$$

$$x_{\alpha_i r} = \max[x \in \mathbb{R} \mid \mu_{\tilde{x}}(x) \geq \alpha_i]. \tag{6}$$

The support $S_{\tilde{x}}$ of a fuzzy variable $\tilde{x}$ is referred to as the α-level set with $\alpha = 0$ (see Fig. 3). The following holds in the case of several α-level sets of the same fuzzy variable $\tilde{x}$:

$$X_{\alpha_k} \subseteq X_{\alpha_i} \quad \forall \alpha_i, \alpha_k \in [0,1] \quad \text{with} \quad \alpha_i \leq \alpha_k. \tag{7}$$

Consequently all α-level sets with $\alpha > 0$ are subsets of the support $S_{\tilde{x}}$.

3.2 α-*level optimisation*

The α-level optimisation is based on discretization of all fuzzy input variables $\tilde{x}_n, n = 1, 2, \ldots l$, and fuzzy output variables $\tilde{z}_p, p = 1, 2, \ldots m$, with the same number of α-levels α_i, i = 1, 2, …, q. The α-level set X_{n,α_i} on the level α_i is assigned to each fuzzy input variable $\tilde{x}_n$. All α-level sets X_{n,α_i} form the l-dimensional crisp subspace $\underline{X}_{\alpha_i}$. Mutual dependencies or rather interactions between fuzzy variables can exist. Without interactions the subspace $\underline{X}_{\alpha_i}$ forms an l-demensional hypercuboid, otherwise the hypercuboid forms the envelope: holes within $\underline{X}_{\alpha_i}$ are possible. On the same α-level the crisp subspace $\underline{X}_{\alpha_i}$ is assigned to the crisp subspace $\underline{Z}_{\alpha_i}$, which is formed by the α-level sets Z_{p,α_i} from the fuzzy output variables $\tilde{Z}_p$.

Each point of $\underline{X}_{\alpha_i}$ can be described by its coordinates x_1, x_2, …, x_l. The computation of $\underline{z}$ = (z_1, z_2, …, z_m) can be carried out by means of any mapping $f(\cdot)$:

$$\underline{z} = f(\underline{x}) = f(x_1, x_2, \ldots x_l), \tag{8}$$

where $f(\cdot)$ is referred to as the deterministic fundamental solution. Under the condition of convex fuzzy variables it is sufficient to calculate the smallest and the largest element of Z_{p,α_i} for a sufficient number of α-levels. Therewith the membership function $\mu_{\tilde{z}_p}(z_p)$ is given in a discretized form.

Finding the minimum and maximum elements is an optimisation problem with the objective functions

$$z_p = f(x_1, x_2, \ldots x_l) \Rightarrow \min \text{ and} \tag{9}$$

$$z_p = f(x_1, x_2, \ldots x_l) \Rightarrow \max, \tag{10}$$

where $(x_1, x_2, \ldots x_l) \in \underline{X}_{\alpha_i}$.

Figure 4 illustrates the procedure exemplarily for l = 2 fuzzy input variables $\tilde{x}_n$ and m = 1 fuzzy output variable $\tilde{Z}_p$.

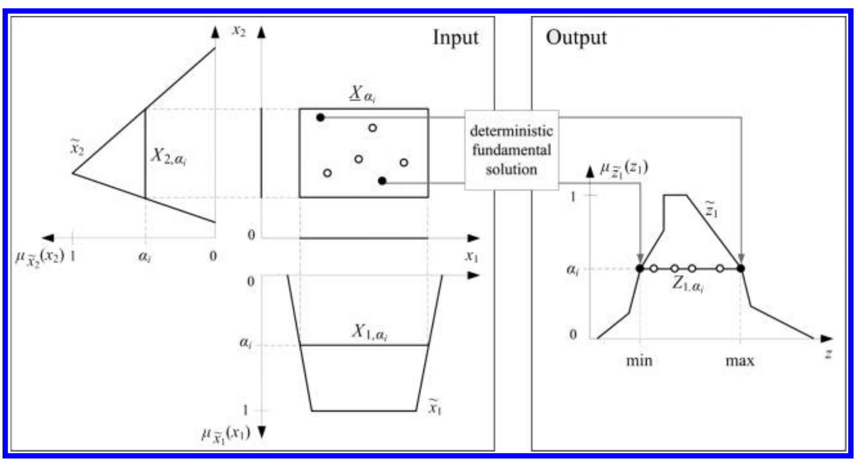


Figure 4. Fuzzy analysis using α-level optimisation on α-level α_i.

4 EXAMPLE

In the following, a practical application of fuzzy analysis and α-level optimisation respectively is demonstrated using the simulation program AnyLogic® and its integrated Monte Carlo Simulation as well as the Java OptQuest™ optimizer.

The logistics of a virtual building site is investigated regarding pre-fabricated columns, the total duration of their delivery process is to be analysed. The modelled scenario is as follows: A factory produces columns and several trucks deliver them to the building site. A crane lifts the columns from the trucks to a storage place. If the crane is busy, the trucks make a one-time detour to another building site.

The average velocity of the trucks is characterized by uncertainty. No statistically firmed data are available, only the expert knowledge of the truck drivers. They can roughly estimate the approximated velocity on the route and the velocity they will not exceed or fall below. Therefore the velocity of the trucks is modelled as fuzzy input variable $\tilde{v}_{in}$. It is defined as normalized triangular fuzzy number $\tilde{v}_{in} = \langle x_l, x_p, x_r \rangle$ where x_l and x_r are the velocities they will not exceed or fall below, i.e. the left and right boundaries of the support $S_{\tilde{v}_{in}}$. Furthermore x_p is the speak value ($\mu_{\tilde{v}_{in}}(x_p) = 1$), which corresponds to the velocity estimated as accurately as possible by the driver. The examined fuzzy output quantity is the total duration of the described process.

4.1 *Implementation*

The considered process is modelled within the simulation program AnyLogic®. Fuzzy analysis is not implemented in AnyLogic® originally, so two variants of α-level optimisation were realized: α-level optimisation by means of the Monte Carlo Simulation with its graphical output (see Fig. 6) and alternatively applying the integrated optimizer. A text output of the minimum and maximum values for every α-level set is produced using the Java OptQuest™ optimizer. In both cases the provided solutions are only approximations, but the optimizer computes the extreme values numerically more efficient.

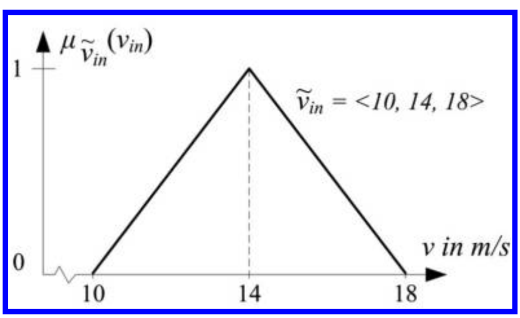


Figure 5. Fuzzy input variable $\tilde{v}_{in} = \langle 10, 14, 18 \rangle$.

The number of trucks no_{truck} and the number of columns no_{column} are deterministic input parameters and known in advance. The implemented algorithm allows to choose the amount of α-level sets, which are defined automatically equally spaced within the interval [0,1]. The fuzzy output variable $\tilde{t}_{out}$ is the total duration of the delivery. In general case the result $\tilde{t}_{out}$ is a polygonal fuzzy number (see Fig. 6).

Because fuzzy analysis is not implemented in AnyLogic® originally, each α-level α_i is represented by a uniformly distributed random variable within the interval

$$[x_l + \alpha_i \times (x_p - x_l),\ x_r - \alpha_i \times (x_r - x_p)] \tag{11}$$

Using Monte Carlo Simulation the α-level optimisation is carried out as an undirected search within the input subspace, which leads to bad results for high-dimensional problems. The intrinsic optimisation algorithm then yields better approximations for the extreme values for each α-level.

4.2 *Results*

The result of the fuzzy analysis by means of the α-level optimisation is the fuzzy output variable $\tilde{t}_{out}$. Initially this variable provides information about minimum and maximum duration of the associated process on the examined α-levels. By using the Monte Carlo Simulation instead of the optimizer all computational results between the extreme values are displayed too. As the Monte Carlo Simulation is an undirected search with uniformly distributed input values within each α-level set, some additional information can be inferred in some cases.

Different configurations were analysed using the Monte Carlo Simulation. Figure 6(a)–(e) shows somse characteristic fuzzy output values $\tilde{t}_{out}$ with $no_{truck} = 5$, $no_{column} = 20$ and $q = 5$ α-levels.

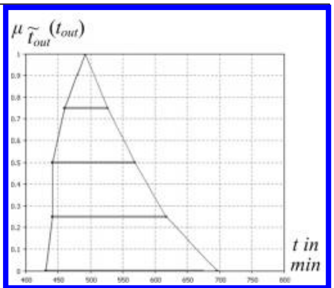
Figure 6 (a) presents a fuzzy result of a 1-dimensional optimisation problem. The fuzzy velocity $\tilde{v}_{in}$ (see Fig. 5) is the same for all empty as well as for all loaded trucks, there exists an interaction between them. This scenario is conceivable when the trucks drive at nearly the same time and therefore the traffic conditions are similar too.

On the other hand Figure 6(b) represents a 25-dimensional optimisation problem. Each truck has its own fuzzy velocity $\tilde{v}_{in,1 \ldots no_{truck}}$ when it is empty and another fuzzy velocity $\tilde{v}_{in,1 \ldots no_{pillar}}$ on

(a)

1-dimensional optimisation problem

all empty and loaded trucks: $\tilde{v}_{in} = \langle 10, 14, 18 \rangle \frac{m}{s}$

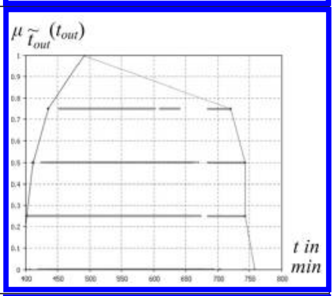


(b)

25-dimensional optimisation problem

empty truck: $\tilde{v}_{in,1\ldots no_{truck}} = \langle 10, 14, 18 \rangle \frac{m}{s}$

loaded truck: $\tilde{v}_{in,1\ldots no_{column}} = \langle 10, 14, 18 \rangle \frac{m}{s}$

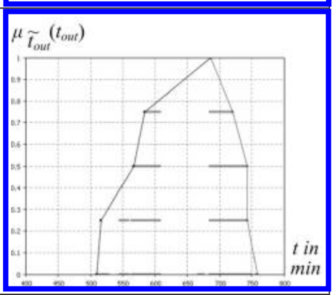


(c)

1-dimensional optimisation problem

all empty trucks: $\tilde{v}_{in} = \langle 10, 10, 10 \rangle \frac{m}{s}$

all loaded trucks: $\tilde{v}_{in} = \langle 10, 14, 18 \rangle \frac{m}{s}$

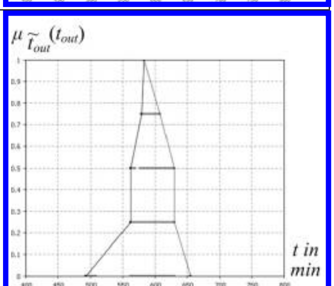


(d)

1-dimensional optimisation problem

all empty trucks: $\tilde{v}_{in} = \langle 12, 12, 12 \rangle \frac{m}{s}$

all loaded trucks: $\tilde{v}_{in} = \langle 10, 14, 18 \rangle \frac{m}{s}$



(e)

1-dimensional optimisation problem

all empty trucks: $\tilde{v}_{in} = \langle 14, 14, 14 \rangle \frac{m}{s}$

all loaded trucks: $\tilde{v}_{in} = \langle 10, 14, 18 \rangle \frac{m}{s}$

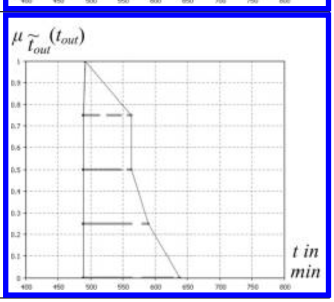


Figure 6. Fuzzy results $\tilde{t}_{out}$; $no_{truck} = 5$, $no_{column} = 20$.

every new transport job. There exist no interactions between the fuzzy input variables. This scenario is conceivable when the trucks drive at different times and therefore the traffic conditions are not comparable. It is evident that the fuzziness is larger than in case (a).

The Figures 6(c)–(e) are again 1-dimensional optimisation problems and have special characteristics. The velocity of the loaded trucks is the fuzzy number $\tilde{v}_{in}$, whereas empty trucks by contrast have a crisp velocity each $(10, 12 \text{ or } 14\, m/s)$. This modelling approach might be chosen when the fuzziness of the velocity results from the possibility of checks for example at national borders, building site entrances or by the police on motorways. Usually such checks are conducted when trucks are loaded. Therefore only the velocity of loaded trucks may be modelled as fuzzy variables.

The results of the configurations (c)–(e) substantiate the importance of a correct assignment of all variables and parameters: Although the crisp velocity on the way back is the only difference between the three variants, quite different membership functions arise.

In Figure 6(c) the output variable $\tilde{t}_{out}$ contains holes over all α-levels and therefore the displayed membership function is only the convex hull of the actual non-convex membership function. Consequently there is a time interval where it is impossible that the process finishes–with the given input values no results within this interval do exist. Using enhanced methods also non-convex membership functions can be obtained (Reuter 2008). Figure 6(e), however, represents a result where for all α-levels nearly the same certain minimum process duration applies, although the fuzzy input variable is a symmetric triangular fuzzy number.

In general it can be inferred which impact the reduction of the fuzziness of the input variables has on the fuzziness of the output variable. Sometimes it is possible to reduce the fuzziness of the input variables for example by additional investigations. Figure 6(d) is an example where it can be profitable to reduce the fuzziness of the velocity even only slightly to the boundaries given by α-levels $\alpha = 0.25$ with the result that the fuzziness of the total duration will be reduced about the half.

5 CONCLUSION

In this paper a practical application of fuzzy analysis by means of α-level optimisation is presented. Therefore two implementations within the simulation program AnyLogic® are suggested. By integration of uncertain data into different models of building industry more realistic forecasts by means of simulations are received.

A simulation using fuzzy input variables results in a fuzzy output variable equally. In comparison to a deterministic simulation a gain in information is achieved thereby. Furthermore the form of the membership function can provide additional information.

The noticeable differences between the fuzzy output values of the concrete example substantiate the importance of a correct assignment of all input variables and parameters within process modelling or simulation.

To obtain non-convex membership functions as well, enhanced methods have to be used.

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Extending functionalities of Management Systems to CityGML

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ABSTRACT: Usual approaches to GIS (Geographic Information Systems) to AEC (Architecture, Engineering and Construction) environments follow a strategy where raster information is referred to vector data. The large diversity of business models, processes, services and applications makes very difficult to share or exchange information and there is an increasing need of software tools and related developments for interoperability. Currently, it is commonly acknowledged that a semantic approach is the key for identifying contents, sharing and generating knowledge, from different repositories. Some increasingly accepted standards are based on Industry Foundation Classes (IFC) and the CityGML framework. In this work we present an extension of CityGML framework for incorporating precise geometric information arising from 3D laser, and a drastic simplification of very large linked models by using the extraction of dominant planes. The local modelling follows a methodology similar to the used in Computer Vision with processing and analysis stages; the output is a collection of polygonals of dominant planes. We have adapted an advanced Visualization tool (based in Collada standard) for managing additional information linked to relational databases, and connecting with web-based applications for simplifying communications between office and workplace. The software application has been developed for management of interventions for solving Accessibility issues in Cultural Heritage urban environments and, currently, it is being adapted to Integral Rehabilitation interventions in Social Housing.

1 INTRODUCTION

Information and management about the urban 3D models is a topic of high relevance nowadays. The buildings 3D modelling is one of the most significant areas for the documentation systems development, reporting and management of urban heritage. The large volume of information content in digital repositories linked to GIS has led development of computational tools that allow simplify the scenario representation and management at different levels of details.

The development of an integrated solution for process and services management is a highly complex from a methodological point of view, in a first phase is necessary to adopt a strategy based on processes, while in a second phase (which is not present here) the strategy will focus on the provision of services. A methodology based on process requirements is associated with information, communication and standardization activities of intervention processes. Therefore, the specification of protocols plays a crucial role. In this process framework is necessary to solve problems relating to the environment (physical space for the interventions), the types of users (technicians, disable people or citizens in general) and different types of tasks (operations on the space, to facilitate the provision of services such as location and guidance, for example). The three areas are divided into a context that is organized around "events" (physical or digital it is necessary identify and write down). A collection of events is a sequence whose validation generates a product that should meet the relevant requirements for the exchange to facilitate interoperability between tools. Accessibility solve the problems related to the organization of a sequence to structure (relations between events) and their functions (related to the task carried out in physical space and services related to such tasks). The geometric framework provides support environment for describing the structure (relationships between components) and their features (use of space by different users). Semantics provides a link between the support, structure and functionality.

From the viewpoint of Administration and more general users (not necessarily involved in construction activities), it is necessary to exchange information and knowledge between different agents and solutions to a larger scale involving urban districts or the whole city. This task concerns mainly to Knowledge Management Systems to urban scale. City Geographic Mark-up Language (GML3) is an OGC (Open Geospatial Consortium) standard data model and XML-based format for the storage and exchange of virtual 3D city models for exchanging data by using ontologies.

This paper aims to contribute to an integrated approach to managing processes and services based on different ontologies [Kuh01] [Gom04], which are all referred to the space environment. Similar to the SIG, we adopt a strategy with multiple hierarchies, but in which all information is calculated on a space-time geometry model, i.e., a model that is updated over time from the interaction with different types of users.

The most important precedent for the approach taken in this work is given by CityGML. It is a common information model for representing 3D urban objects using a modular approach to integrate the "uprising", planning and simulation of interventions, and includes a growing number of applications in different technology domains.

In this work, we have developed an approach which is based on 3D urban surveying arising from laser scanning [Fue06] files in urban environments. A laser scan device provides dense clouds of points where the system stores geometric (3D position in some coordinate system) and radiometric (grey level intensity or 3D colour) information for each point. Data capture provides a dense information of scanned zones, with a density which can be selected by the user; resulting files can contain from several hundreds thousands to millions of points. Next, clouds must be "aligned" by means of a very precise methodology to avoid errors in models; depuration to avoid redundancies is necessary. However, irregular distribution, shadows and the very large volume of information arising from matching poses some problems related to modelling, surveying and management of resulting models. Furthermore, there are increasing needs for providing accurate feedback between workplace and office for documenting and georeferencing modifications which are holding at workplace; modifications at workplace must be adequately surveyed, sent to and evaluated by central office for his (dis)approbation and insertion in Information System.

We have developed the software application GIRAPIM [JCa10] for the information management of range-based models to different resolutions for buildings and urban environments. GIRAPIM is a tool designed to exploit 3D information system for urban environments. In our case, urban environments are documented using LIDAR technology for some Areas of Integral Rehabilitation in Small Villages of Palencia (Spain); the information has been captured with Ilris 3D (Optech). To allow the information management at workplace and provide the capability of making consults with mobile devices, it is necessary a drastic reduction of models. However, resulting models are still georeferenced to the accurate original model, and modifications performed by users of our application are inserted in the remote repository for consulting or updating information. CityGML provides the framework for inserting information to different LoD. Advanced visualization (including facilities for interactive navigation or insertion of annotations, e.g.) of simplified model is performed by using Collada [Bar08]. In our case, our software application uses some functionalities of CityGML, Collada and some applications linked to Google for managing information in a intuititive way, thanks to the use of ordinary language (semantic layer). In this way, this application provides a support for technicians, which is being adapted to provide more general services to citizens in general, including some solutions relative to Accessibility Issues to Cultural Heritage in urban environments.

Below are some basic elements of ontologies that facilitate the organization and management of the Information using Citygml with usual framework. Section 3 shows the advantages for geometric referencing available information concerning the processes of intervention and services for different types of users. The general principles of GIRAPIM platform are presented in Section 4. Finally, we present some conclusions and future work lines.

2 INFORMATION SYSTEMS IN AEC ENVIRONMENT. CITYGML

Our multi-system approach includes three systems involving Documentation, Information and Management System which are superimposed to the initial different tasks (surveying, planning, intervention, and maintenance) like it is showed in Figure 1. The above three Systems can be considered as "very large layers" which are superimposed

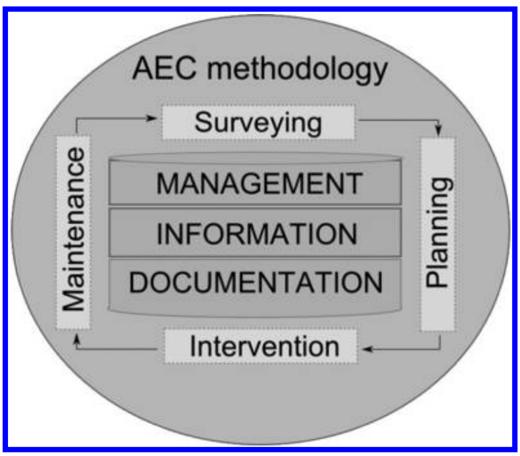

Figure 1. Overview of systems and AEC task.

as successive steps with an increasing complexity; in particular, Documentation System provides the support for Information System, and this one for Management System, with their corresponding geodatabase for storing, updating, processing and analysing information which must be translated in new knowledge about the environment.

Traditional three-dimensional Geographic Information Systems (3D GIS in the successive) include two kinds of data, where raster information is geometrically referred and managed in terms of vector data. The design and implementation of multiple articulations between the above three systems (Documentation, Information and Management) requires a semantic approach for the knowledge management. A semantic approach provides a support for interactions between different agents in terms of ordinary language with keywords which are structured according to acknowledged deffnitions (thesauri) and logical rules (taxonomies).

CityGML [Kol08] is an urban environment data model for managing the information likely to be represented on a geometric support. CityGML provides the framework for developing applications focused towards planning and executing (conservation or rehabilitation) interventions in Cultural Heritage buildings or to provide services.

The City Geography Markup Language (CityGML) is an innovative concept for modelling and exchange 3D city models, which has been adopted as a international level (OGC standard) from October 2008. CityGML is based on a rich, general purpose information model in addition to geometry and graphics content. Additionally, CityGML has been developed as a semantic Framework[1] for 3D city model extending traditional functionalities of 3D urban GIS. It provides a support for making easier interoperability between different applications; CityGML does represent geometry and graphical appearance of city models. Furthermore, it contains features for representation of the thematic properties, taxonomies and aggregations. CityGML supports different levels of details (LoD) for the information representation, which are grouped in 5 groups. LoDs are independent of the data collection process, and consequently; consequently, visualization and information exchange are independent modules with information.

CityGML it is a multifunctional model which can be used for data storage, database modelling, data exchange. In resume, it provides a basis for advanced 3D geospatial information system which can be used without being a GIS expert, thanks to its semantic management in terms of a well specified Ontology. Ontology is given by a lexicon (collection of key words), a thesaurus (a collection of definitions) and taxonomy (collection of logic rules); all of them are specified in an entity-relation diagram which is in charge of supporting the knowledge management. Neither of them is unique and must be specified for each physical space, type of users and tasks to be developed by users. In our case, we have designed an ontology to facilitate interoperability among the tools that affect the different systems (3D Documentation, Information and Management) and functions (processes and services); see more in [Mar10]. For such specific knowledge domains, CityGML provides an extension mechanism to enrich the data and relate it with the CityGML standard features under preservation of semantic interoperability.

CityGML semantics provides a general framework to articulate aspects of entities, the structural relations and the role played by these entities-relationships in complex systems. To facilitate the cooperation between different information systems, it is necessary design a service and a process manager over the 3D models. Thus, our solution intends to improve communication between different agents and ensure interoperability between different software tools and platforms linked to different information systems in urban environments in terms of a semantic approach.

3 3D INFORMATION MODELLING

Information Processing and Analysis are the first stages of 3D modelling of buildings and small urban zones. We have developed building 3D modelling techniques which are based in image or range-based information. The software application GIRAPIM is focused on hybrid modelling, CAD modelling and rendering tools for visualization. The hybrid character for modelling concerns not only to the different nature of inputs (rectified images and clouds of points), but also from the reconversion of discrete digital information to continuous one,explain it in [Fin10]: clouds of points are grouped in dominant planes (corresponding to the ground, façades and roofs, initially) which are grouped in polytopes given by connected polygonals of dominant planes (see Fig. 2).

The detection of 3D primitives from the discrete information (dense points cloud) follow a similar approach to the 2D case: filtering, local analysis and clustering (critical parameters: linearity and proximity of directional vectors).

[1] A semantic framework should be a formal system which abstracts core notions which are shared by the various approaches to natural language semantics which are offer. [Ro93].

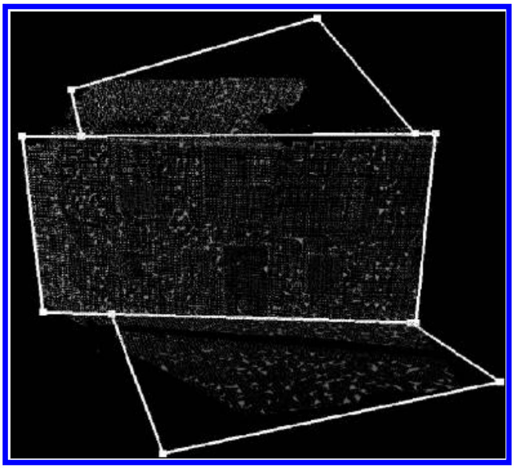

Figure 2. Semiautomatic dominant plane detection. GIRAPIM.

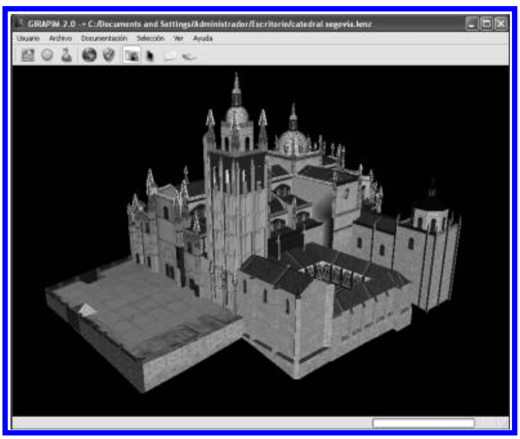

Figure 3. Complex building model CAD loaded in GIRAPIM.

GIRAPIM provides a module for semi-automatic detection of dominant planes from dense clouds of points, as has been seen in the previous figure. Grouping of dominant planes is performed by typology of dominant plane (ground, façade, roof), by adding a restriction of adjacency; the resulting object is called a urban polytope which corresponds typically to a block bounded by a collection of streets to the ground level. Next step is the use of this polytope for generating an urban model volumetric segmentation, ie the decomposition of the 3D scene in a finite union of isolated urban polytopes. The subsequent urban model generation is delegated to CAD tools through GIRAPIM interoperability with Google SketchUp (DXF and COLLADA formats).

Our application works with models of buildings based on a CAD (see Figure 3), managing different levels of complexity at different levels of detail (LOD), depending on the application complexity on which you will use. Our application can use any standard model based on Collada standard.

Our multiresolution approach allows managing models at different resolutions which are compatible between them and with several levels of complexity going from a simple cube model based on the detection of dominant planes to a complex model of a cathedral formed by a triangular complex mesh (both correspond to the same object to different LoD).

After detecting dominant planes, the next step is to define the provision of services related to information systems for 3D AEC (Architecture, Engineering, Construction) environments. Traditional CAD tools (Google SketchUp, Maya, 3D Studio, Blender…) have not incorporated semantic contents; semantically not identify geometric elements, but the CityGML framework allows performing semantic annotations according to the previously specified lexicon. The development of Ontology is in charge of knowledge management, after inserting the information onto the extended CAD model. In this way, each geometric object supports an additional semantic information which can be independently collected for surveying or reporting specific issues regarding in our case to Accessibility or Rehabilitation and Conservation tasks in urban environments. Our system allows any user to perform a interactive semantic labelling associated with 3D geometric model. This labelling is based on the lexicon of CityGML and the extension of our domain ontology.

4 SYSTEM FEATURES

An additional goal is to be as independent as possible with respect to data capture, monitoring infrastructures, operative systems and proprietary formats. All primitives for supporting radiometric, geometric and superimposed semantic information are supported or generated from points with grey-level or colour information; in other words, they are given by a collection of lines in plain text or ASCII format. Monitoring and communication systems are a bottleneck, due to the existence of a large number of commercial solutions; nevertheless, our solutions are compatible with two extended supports for services in urban environments such as Wifi and Bluetooth in indoor environments, and GPS (and its variants) for outdoor environments; 3G-based solutions are currently being developed for more advanced and expensive mobile devices. In other words, the software application GIRAPIM uses only open standards for interoperability and exchange of information in Web by using Internet resources. GIRAPIM interoperability are described in section 4.2.

GIRAPIM decomposes it into the following structure: display engine, CityGML manager and a remote repository. The next figure illustrates a global overview of GIRAPIM architecture (Fig. 4).

4.1 *System features*

GIRAPIM is a client desktop tool because in Cultural Heritage domains it is necessary to have a very accurate model for information management by technicians. Furthermore, it is desirable to have lower resolution models with added information which can be explored and consulted by citizens in general. In Fig. 4 one shows some connections between different components with an emphasis on the viewer, the database and CityGML module. Next, we shall will briefly describe each one of them (the item number of the enumeration correspond the same number in Figure 4):

1. *3D Viewer Engine*: enables visualization of semantic annotations and model geometry in 3D. Based on OpenGL rendering technology (also a Khronos Group standard) it shows the information overlaying different layers: geometry and semantic. This module is responsible for picking and selection of objects in the scene with the mouse.
2. *Patrac repository*: designed to support at the same time CityGML vocabulary and PATRAC ontology. This is the central repository of contents for scenarios where accessibility problems are detected. This database is supported by PostgreSQL database management system with PostGIS extension enabled to mange GIS information.
3. *CityGML manager*: this module is responsible for create CityGML compliant output data. This job could be done thanks to PATRAC ADE extension developed for CityGML. Basic CityGML entities and PATRAC ADE cover completely the vocabulary of PATRAC ontology so the same information can be exported with the same meaning it has in database (see Fig. 5).

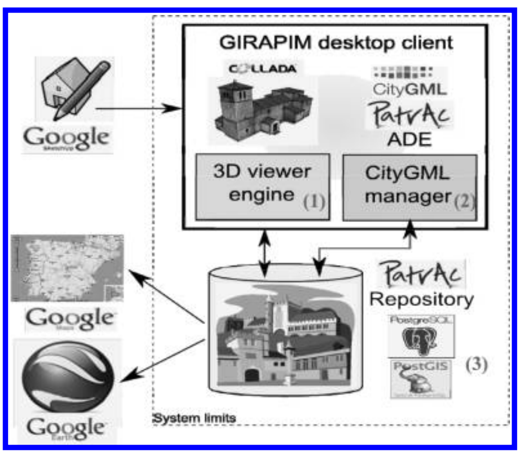

Figure 4. Overview of GIRAPIM global architecture.

4.2 *Interoperability*

COLLADA (COLLAborative Design Activity) is an open interchange file format for interactive 3D graphics, managed by the Khronos Group consortium. It defines a XML schema for exchanging digital graphics between applications. Originally created by Sony, today is shared between Sony and Khronos Group and it is supported by many game studios, graphic engines and modelling software (e.g. 3D Studio, Maya or CityEngine). GIRAPIM is intended to be a tool for semantic annotation of less or more complex models so it delegates model task in specialized free or commercial software (see in Fig. 3 an example of load a complex model in GIRAPIM). COLLADA files (with extension .dae) are imported and viewed in GIRAPIM and models are used to detailed heritage representation, especially inside of the monument. GIRAPIM also support Google Earth (.kmz) file import.

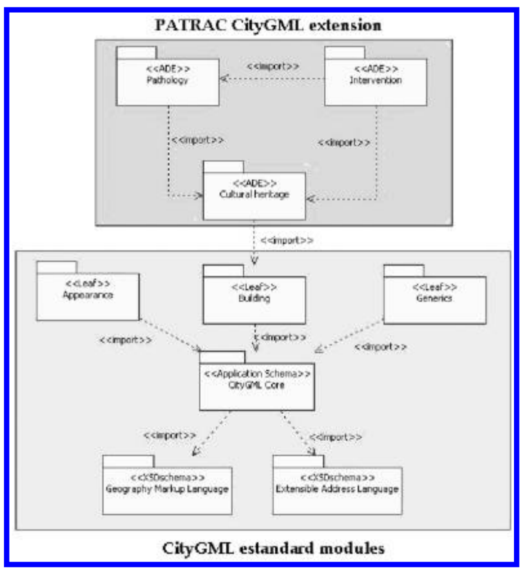

Figure 5. Our CityGML extension for cultural heritage domain.

Due to KMZ files contains COLLADA models (adopted since version 4.0 by Google Earth) user can annotate models that after they visualize and navigate in Google Earth. This can be done in any web browser with Google Earth plug-in installed in order to simplify the access and visualization to semantic information. Moreover the KMZ files can be easily generated with Google Sketch Up tool, freely accessible by anyone like Google Earth. The same information can be showed in Google Maps in 2D what enables quickly mobile access to the information.

Semantic annotation enables translation from 3D geometric model data to 3D semantic model in CityGML. Therefore, CityGML includes geographic position of the semantic information in a dual-view approach in order to support many task such as spatial reasoning, problem detection or 3D context-based information provision. Semantic vocabulary, structure knowledge and relationships for Knowledge management has been developed independently in PATRAC ontology which supports reasoning tasks while GIRAPIM provides data access used along the reasoning.

5 CURRENT DEVELOPMENT AND NEXT FUTURE STEPS

The main contribution of software built GIRAPIM concerning: 1) the incorporation of metric accuracy (obtained from terrestrial photogrammetry and 3D laser) to the framework of CityGML, 2) the design and implementation of software tools for the simplification of models based on the semiautomatic dominant planes detection, 3) the development of web services for knowledge management (including capture, storage and transfer) for interventions in buildings, 4) interactive 3D visualization access, updating and management of urban database on rehabilitation work. The application GIRAPIM has been applied to Areas of Integrated Rehabilitation (ARI), small urban districts in Spain, with interest from the standpoint of Cultural Heritage, but can be applied to the inspection of statements on all types of buildings, including housing, too.

In the next future, thanks to created data scheme and information repository, a large amount of Web services could be develop to offer other capabilities such as mobile agenda intervention management for architects and technicians, accessibility problems automatic notification to users or a collaborative approach to contents creation where users could send detected accessibility problems. GIRAPIM is the germ of a larger reaching applications for different tasks linked to 3D urban information systems, including accessibility and conservation or restoration tasks in Cultural Heritage domains, but with a larger potential. Web services and mobile computing are being developed independently, but connected to GIRAPIM software application. Support mobile based services require to solve some problems such as 3D visualization in mobile devices (probably thought Web3D standards), reduces CityGML information (due to XML representation) and altitude sensor in handheld devices for 3D positioning. All of them are already in an advanced stage of development and will be reported in the next future.

6 CONCLUSIONS

GIRAPIM is a tool developed to enable interactive semantic annotation for interventions surveying in Cultural Heritage urban environments, including functionalities linked to conservation and restoration, and with system assistance. In order to improve interoperability with other tools it uses open source technologies and standard formats to represent the information. GIRAPIM is intended to be user-friendly and run in laptop or desktop computers, but semantic information can be accessed through Web services. In this sense, the software architecture is separated into 3 loosely coupled modules: a viewer, a remote database and a CityGML manager. The database is the central PATRAC repository and provides access to resources to other services.

ACKNOWLEDGEMENTS

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Towards a semantic-based approach for the creation of technical regulatory documents in building industry

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ABSTRACT: This paper gives an overview of a formal semantic of creation of technical regulatory document in the Building Industry. In the current context, it is urgent and crucial to facilitate the creation of regulations. We focus on Technical Advice delivered by the French scientific and technical center for building and we propose semantic services based on Semantic Web models and techniques to support their creation.

1 INTRODUCTION

Regulations in the Building Industry are becoming increasingly complex and involve more than one area. They cover products, components and project implementations. They also play an important role to ensure the quality of a building, its features and to minimize its environmental impact. For 30 years, CSTB proves its expertise in this field through the development of the complete encyclopedia of French technical and regulatory texts in the domain of the construction: the REEF[1]. In the framework of collaboration between CSTB and the I3S laboratory, we work on the acquisition of knowledge from technical and regulatory information contained in the REEF and the automated processing of this knowledge with the final goal to assist professionals in the creation of new texts.

The French scientific and technical center for building, CSTB[2], with other actors, has launched the "Grenelle Bâtiment 2012"[3] initiative which aims to change the rule book. This regulatory change must be done within the framework of a comprehensive approach that takes into account both the complexity of the construction sector and the plurality of uses and needs, and other existing regulations in the interests of consistency and non-contradiction.

[1] http://publications.cstb.fr/cdreef.asp
[2] Centre Scientifique et Technique du Bâtiment, http://www.cstb.fr/
[3] http://www.lemoniteur.fr/135-planete/article/actualite/519868-grenelle-de-l-environnement-toutconcentrer-sur-2012-dans-le-neuf

In this paper, we focus on the creation of technical advice ("avis techniques" in French or ATec) and we present our approach to support their creation since the arrival of a manufacturer document at CSTB until the certification of its product and the deliverance of a technical advice by CSTB experts. In the next Section, we present the context of our work: we describe the regulations we work on and the material available at CSTB. We describe in Section 3 our objectives, we detail in Section 4 our overall approach to support the writing of technical advice. We conclude in Section 5.

2 CONTEXT

2.1 *Technical and regulatory texts*

The Building Industry is regulated by many rules. We distinguish between official texts and technical texts. Official texts are either mandatory (their execution is mandatory) or informative (they describe "best practices" or requirements advised by construction professionals). Building codes expressing these two types of requirements can then be divided into prescriptive and performance codes [Satti, Krawczyk, 2004].

Technical texts are standards (NF, EN, ISO standards), technical advice, assessments of technical experimentations, etc. They define solutions for technical problems on products, services and procedures, and guarantee their quality and their effective use. In our work presented in this paper, we focus on a particular type of technical texts, namely Technical Advice. We analyzed their structure and content to propose a way to standardize their format through the implementation of adapted semantic services.

Technical Advice is authorized opinions on the construction procedures, materials, products, which are new or innovative and not yet normalized. In CSTB Technical Advice is written by expert and indexed and stored in databases by librarians; they are examined by the specialized groups (GS). The role of these groups is to study the technical file made by manufacturer and approve the product if it conforms to building industry laws.

A Technical Advice consists mainly of three parts: (i) layout page, (ii) the technical advice, (iii) the technical description.

The Layout Page page brings together various elements of an administrative nature, constituting what might be called a descriptive list of the Technical Assessment. These elements are at least:

- The number of technical advice (TT/ Vintage—N°);
- The name of the product family which is attached to the product (or process) in three languages (E, D);
- The trade name of product;
- The identification and contact the owner of the Technical Advice;
- Identification Specialist Group which formulated Notice;
- The recording date of the Technical;
- Other information relating to the publishing of the notice and publisher (CSTB).

The technical advice itself comprises three parts: (i) Brief definition, (ii) the advice, together with the findings define by GS and the period of validity, (iii) the additional remarks from the GS.

The Technical File is prepared by the applicant, following indications reporter's request, and is divided into three parts: (i) description, (ii) experimental results, (iii) References.

The librarians who index Technical Advice are obliged to respect the format of the layout page and the technical advice. Finally a Technical Advice is stored in PDF format in the CSTB database.

2.2 *Actors of the building industry*

As it appears in the simplified nomenclature described above, several actors interact in the development of building regulations. These are issued by standards bodies such as AFNOR or by departments. CSTB plays a major role in the development of technical texts: it met the study commissions working to develop technical advice applying the standards for reporting of product or component supplied by the industry.

CSTB plays a major role in the dissemination of all regulations. It publishes various guides for use by professional's construction, including [Gregory & Cibien, 2005] which aims to help professionals to understand better all the rules of construction to best applied.

For this, librarians are concerned with regulatory monitoring and restructure the regulations in useable by the tools of regulatory applications of CSTB.

2.3 *Knowledge available at CSTB*

CSTB is involved in regulation dissemination and has to encourage professionals to use it as leverage. For the past 30 years CSTB has been the French leader for the dissemination of knowledge on Architecture, Engineering and Construction (AEC), through its digital AEC encyclopedia (REEF). But today new powerful tools are emerging from research on Knowledge Management and Semantic Web.

Our work takes place within the framework of the "Semantic REEF" action launched by CSTB which aims to study how Semantic Web models and technologies can facilitate the work of professionals in information retrieval.

As a first result we managed to apply an inference engine on REEF encyclopedia thanks to a new semantic model.

The classification of the Information in the REEF is based on the retrieval of semantically close knowledge inside atomic information blocks, which are indexed by a special conceptualised terms. One of the first implementations of this approach was the classification in the CDREEF [Maïssa et al, 2002] based on units of secondary information (UIS131).

At CSTB, technical advice are written by experts and later indexed by librarians who store them in a database.

By studying this technical advice and their associated metadata and by interviewing experts and librarians, we have identified some recurrent technical and regulatory knowledge expressed by CSTB experts and we have concluded that partially automating the drafting of these documents was possible.

2.4 *Semantic REEF*

We work at present on the establishment of one unified terminology to describe and ease the information retrieval on technical regulation. The REEF aims to show the efficiency of semantic web tools applied to AEC[4] regulation dissemination.

The corpus of technical regulatory REEF has a volume of about 3000 documents and growth of

[4] Architecture Engineering and Construction.

10% per year. It is currently distributed on DVD and Intranet.

The production process of the corpus of Reef involves two main steps:

– Digitization of documents: Each document corpus is digitized, divided into Information Units Summary (UIS) and then formatted in XML. Each UIS chapter corresponds to a document.
– The integration in the corpus: Each structured document is subject to automatic processing chain, in order to normalize and the other documents related to the corpus.

2.4.1 *Modelling of the content of a document*

The first project to create a format for electronic documents has been launched at CSTB in the 90th to allow the distribution of the REEF in digital format. Noting that the standard formats of electronic documents (DocBook, SGML) does not meet 100% of its needs; CSTB has built a derived XML document.

This format integrates into a single file the concepts of semantics: documentary note, authors' list, preliminary, bodies and sub-chapters, possible appendices as well as the layouts and the internal or external links.

All documents in the corpus REEF are produced or scanned in this format.

The main weaknesses of this format are:

– Its complexity, related to a large number of tags defined;
– Mixing concepts shaping and cutting of the text;
– The mixture between bibliographic information and the contents of the text;
– The loss of semantic tables and figures.

2.4.2 *Modelling of UIS*

The UIS (Unit of Summary Information—The "atomic blocs of information" mentioned in section 2.2) constitute the documentary basic element. But defined also the granularity of the answers brought by the search engine. Within a document, the UIS is organized in a hierarchical way. The UIS represents generally one or several paragraphs of a document (Fig. 2).

2.4.3 *Modelling of vocabulary*

The increasing introduction of document applications for professionals in the building requires that it is based on a common terminology to describe and retrieve information. The meaning of words changes over time (thus the word "accessibility" has taken on new significance with the emergence of laws on equal opportunities), new terms can appear while others become obsolete. It is a

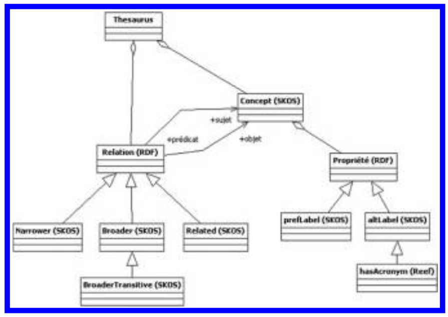

Figure 1. Example of REEF thesaurus formalized with SKOS.

central languages for describing both the contents of documents and the issues of users (humans or machines). The design of such languages raises many arbitrations and poses a real challenge on the conceptual plans and techniques.

2.4.4 *A thesaurus to standard skos*

The standard SKOS is currently the standard suitable to represent the open features of a thesaurus, as shown in the representation of the model indicated above and as illustrated by the example below. The relationships supported are:

– Narrower;
– Broad;
– Related.

These relationships can provide links or dependencies between concepts. With these concepts, SKOS can combine the following properties:

– Word by default to identify the concept (prefLabel);
– Another term to identify the concept—supporting the notion of synonymy and multilingualism (altLabel).

2.4.5 *General modelling of corpus*

You can see in Figure 2 the synthesis of model elements that we discussed above. It shows two main structures are hierarchical and the hierarchy of UIS. Note also the relationship between UIS and concept of the thesaurus. Through these links, we find the ability to index documents and Uis in relation to the semantics they convey. This will apply treatments or arguments on the text by projecting the relationships defined in the thesaurus.

3 OBJECTIVES

As mention in 2.1 and 2.2 CSTB is itself producer/writer of regulatory documents mainly through the production a technical advice.

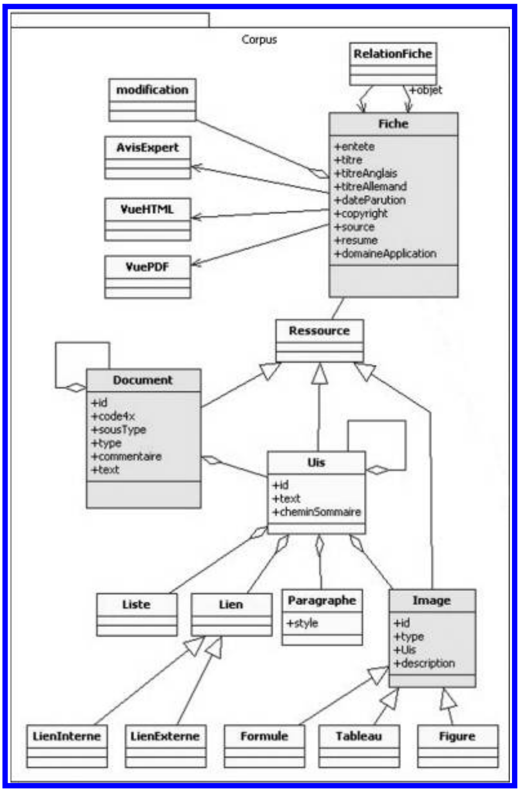

Figure 2. Scheme of corpus model.

The problem regarding production of statutory and regulation texts urges us to look after the possible tracks that facilitate the writing of this texts. In this context of reflection, we take account of constraints already expressed in the existing statutory corpus and of how we can propose a help in this domain using adapted semantic services. It will be a question of developing of:

– Enriched regulation models leaning on ontology allowing at the same time to formalize the knowledge contained in their various regulation texts as well as them hierarchical organization and their interrelations;
– Currently, technical advice are not accessible through the REEF encyclopedia, we manage integrate them into CDREEF.
– Usage models and process models allowing to profile users and their activities in order to give them relevant information;
– Annotation model which will be a structured description for the technical regulatory text and offering more expressiveness and flexibility;
– Algorithms allowing the exploitation of the stemming information of these Models.

4 PROPOSED APPROACH

Currently technical advice are written by CSTB expert and stored in database by librarians in a correct format. Also using tool Apache SOLR[5] CSTB engineers export from Technical Advice database an XML file which contains general information related to them. This export is done automatically each night to update the information. The figure below show a sample of the XML file:

As show in Fig. 3 we can find all the important information mentioned in section 2.1 about the technical advice and other relevant data.

– These elements are at least;
– Validity of the technical advice;
– The path and the name of the Pdf which contains it;
– The identification number of technical advice in the database.

This information will be used to provide search criteria and we can apply an inference engine on it.

4.1 *Conversion of Atec's information from XML to RDF*

Our studies in CSTB showed that it's possible to envisage a mechanism to automate and optimize the creation time of technical advice.

```
<doc>
 <field name="numaff">37</field>
     <field name="typdoss">AT</field>
     <field  name="nom_pro">ELYSEE  Pose
verticale</field>
       <field      name="famille">Bardage
industriel</field>
   <field     name="des_pro">Procédé    de
bardage  en  panneaux    sandwiches  posés
verticalement, comportant des parements en
tôle d'acier revêtu ou inoxydable, et une
âme  en  mousse  polyuréthanne  expansée  sans
CFC.</field>
    <field   name="at_num">2/94-387</field>
<field  name="commen">Il   s'agit  de   la
demande 93515 qui a donnée lieue aux Avis
Techniques 2/94-386 et 2/94-387.</field>
     <field name="an_enr">1994</field>
       <field
name="valide">invalide</field>
       <field          name="adr_pdf">GS02-
C</field>
     <field
name="nom_pdf">AC940387.PDF</field>
       <field name="nom_cli">PAB  PRODUITS
BATIMENT DE SOLLAC</field>
 </doc>
```

Figure 3. Example of XML code extract from technical advice database.

[5] http://lucene.apache.org/solr/

Firstly, we try to use the information extracted from the database in XML format, we find a way to convert this information into RDF format. RDF model is more generic, with a great ability to enrich which are two important points for future manipulation. This model will contain the essential information according to the technical Advice.

To convert the XML file into RDF we use an XSLT filter and convert all the XML fields. Each field will be related to our RDF model to enrich our ontology.

Finally, we automate this process which results in an RDF file update when new technical advice is added to the database.

Currently, RDF file can be applied on CORESE[6] inference engine and with these steps we created an ontology of which contains technical advice.

4.2 *New RDF annotation model for Atec*

We have defined a pattern of semantic annotation of a technical advice including and enriching the metadata currently stored in a database. These annotations are formalized in RDF to ensure their interoperability. They will be used to semantically retrieve technical advice but could also later be used to conduct conformity checking of construction projects. The acquisition of this knowledge is the keystone of other Semantic Web applications that could be developed to support the exploitation of this documentation.

We considered taking the two first parts of the technical advice (Layout Page and Technical Advice part) and retrieving the information which will allow us to have greater granularity of search. We came to the following format:

- The GS (groups)
- The expiration date of the Atec
- The Atec application number
- The type of Atec (New entry or Update)
- The standards to which it belongs
- The domain of the advice.

For the standards and domain of the Atec we use a thesaurus and list of term issued from REEF project.

We have converted the contents of XML file to RDF and we have been able to organize information to make them more processable and we got files as shown in (Fig. 5).

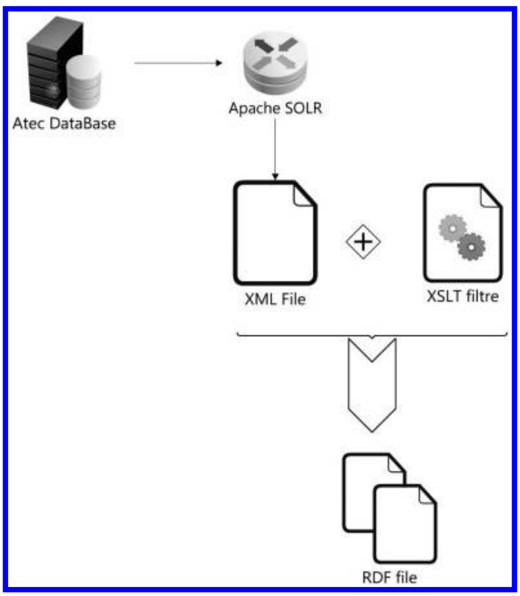

Figure 4. The architecture of the process converting XML file to RDF.

4.3 *The new support the creation of technical regulatory*

The current mechanism of creation of technical advice is too complicated and slow. A lot of people interact in this process. We realized that automating the drafting of these documents was possible. To minimize the time of creation these documents, we opted to create:

- A form which contains all fields necessary to create a standardized format of the technical

```
<Atec rdf:ID="37">
      <num_at>2/94-387</num_at>
      <annee>1994</annee>
      <nomPro>ELYSEE                    Pose
verticale</nomPro>
      <famille>Bardage
industriel</famille>
      <description>Procédé  de  bardage  en
panneaux  sandwiches  posés  verticalement,
comportant  des  parements  en  tôle  d'acier
revêtu ou inoxydable, et une âme en mousse
polyuréthanne         expansée         sans
CFC.</description>
      <valid>invalide</valid>
      <adr_pdf>GS02-C</adr_pdf>
      <nom_pdf>AC940387.PDF</nom_pdf>
      <nom_client>PAB PRODUITS BATIMENT DE
SOLLAC</nom_client>
      <demande>93515</demande>
      <hasChild rdf:resource="#2/94-386"/>
      <hasChild rdf:resource="#2/94-387"/>
      <gs rdf:resource="#2"/>
</Atec>
```

Figure 5. The conversion of XML file to RDF.

[6] http://www-sop.inria.fr/edelweiss/software/corese/

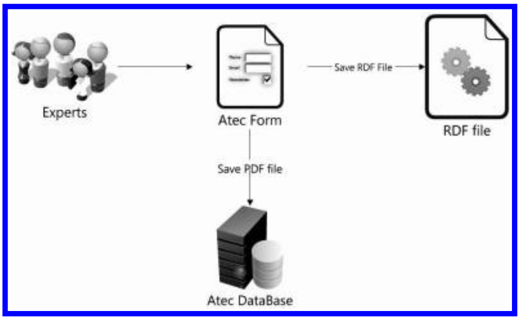

Figure 6. The new support the creation of technical regulatory.

advice. This form will be provisions to industry experts, which contain fields representing information necessary to the technical advice mentioned in section 2.1;

– An RDF file which contains the fields according to the form. All information entered in the form will be used in this model. We construct the RDF model using CORESE or JENA[7]. This ontology is created in a transparent manner from the expert perspective.

Our ontology will be enriched after each insertion of new documents and experts could later be used it to check conformity or perform various semantic searches. We can then optimize our new process for creation of technical advice documents.

Finally, when the experts finish filling in the form fields we have two results:

– A RDF file which contain all information about the technical advice;
– A PDF file conforming to a standard format which is saved in the database.

However, to avoid duplication, the system will analyze the new entries and compare them with those already existing and the expert will have the option to upgrade or insert the new technical advice. With this system we hope to optimize the time creation technical advice, automate drafting there, reduce the number of actors involved in the drafting process and ultimately generate and maintain an ontology with all the essential information on technical advice.

5 CONCLUSION

As a result, we plan to minimize the time and effort of drafting and indexing these documents we have conceived a form to be filled online by CSTB experts. This form will guide the experts in their writing process, it a will enable the automation of the indexing and the control that no information is missing. Also we have defined core ontology to annotate technical advice. It is formalized in RDFS. This ontology will be incrementally enriched by experts while filling in the form guiding the writing of technical advice. Our ontology will be coupled with some domain thesauruses to guide and control the expert when filling in the form. Several are being developed at CSTB among which one seems the most relevant by its volume and its semantic approach: the thesaurus from the Semantic REEF project. It includes a vocabulary of terms used in the building industry and a thesaurus representing standards that can validated the advice. This thesaurus is formalized in SKOS and we plan to combine it with our RDF/S model. We will then be able to propose controlled and "standardised" vocabulary to the expert in order to help him write a new advice.

Finally, we intend to automatically provide experts with the documents relevant or similar to the document being written.

[7] http://jena.sourceforge.net/index.html

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