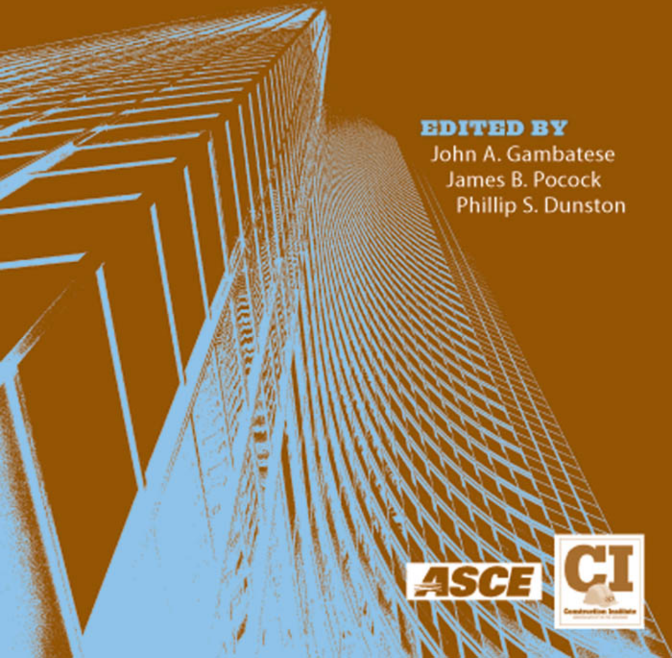
Constructability

CONCEPTS AND PRACTICE



EDITED BY
John A. Gambatese
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CONSTRUCTABILITY CONCEPTS AND PRACTICE

SPONSORED BY
The Construction Institute (CI)
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Foreword and Acknowledgements

Construction is a dynamic, complex, and often dangerous process and industry. One aspect of construction to which many people have devoted thought and effort over the past several decades is constructability. Constructability is often one of the foremost considerations on construction projects. Improving constructability, through the integrated efforts of owners, designers, and constructors, can have great impact on project success. Attaining success through constructability requires knowledge of how it contributes to projects, the obstacles to it being considered and enhanced, and how best to proceed in improving it on projects. This knowledge, however, is not trivial, nor is it universal throughout the construction industry.

The impetus for this publication came out of a recognized need for increased understanding of constructability in the construction industry and a desire to disseminate contemporary research on the topic to those who strive for its continued exposure, development, and implementation. This publication was conceived of and created by members of the Constructability Committee and the Construction Research Council within the Construction Institute (CI) of the American Society of Civil Engineers (ASCE). These groups are composed of construction industry professionals and academicians who are experts in their fields of study and leaders in the construction industry and/or academia.

Initial motivation for this publication was provided by Dr. Keith Molenaar, Associate Professor at the University of Colorado at Boulder who, as Chair of the Construction Research Council and a member of the Constructability Committee, endeavored to develop special publications on various topics, constructability included, for the benefit of ASCE membership and the construction industry. Execution of the publication was carried out by Dr. John Gambatese, Associate Professor at Oregon State University, with the assistance of Dr. James Pocock, Professor at the U.S. Air Force Academy, and Dr. Phillip Dunston, Associate Professor at Purdue University. The Co-Editors, in addition to authoring several of the papers themselves, selected and organized the paper topics, solicited contributions from authors, oversaw and managed the paper review process, and formalized the final contributions and publication. All three Co-Editors are members of the Constructability Committee and Construction Research Council.

Input on the publication content and assistance with reviewing the papers was provided by an Editorial Board composed of highly qualified and experienced construction industry professionals and academicians who are members of the Constructability Committee and Construction Research Council. The Editorial Board members are as follows:

Appreciation is extended to the Co-Editors and Editorial Board members for their input into the publication and thoughtful reviews of the papers. In addition, we would like to thank the paper authors for their unique contributions to the publication. Success and progress in the construction industry is largely a result of the collective wisdom, motivation, and goodwill of those willing to spend a little extra time to discuss and debate topics of interest and communicate their knowledge and expertise to others.

We regard this publication as a beginning and a step forward along the way to greater collaboration and research on constructability. We hope that the experiences, successes, and questions raised by the contributors to this publication will foster additional experimentation, research, and dialogue among all segments of the construction industry. We also hope that continued collaboration will allow us to revisit this topic five or ten years in the future and see genuine progress in the practice of addressing constructability and real improvements in the constructability of construction projects.

John A. Gambatese
Corvallis, Oregon
August 2006

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Introduction

John A. Gambatese[1], Phillip S. Dunston[2], and James B. Pocock[3]

Constructability is a project characteristic that reflects the ease with which a project can be built and the quality of its construction documents. As defined by the Constructability Committee within the Construction Institute (CI) of the American Society of Civil Engineers (ASCE), constructability is:

> "the integration of construction knowledge and experience in the planning, design, procurement, construction, operation, maintenance, and decommissioning phases of projects consistent with overall project objectives."

Construction knowledge and experience are key to constructability. Knowledge of the construction process, the requisite information needed for construction work to effectively and efficiently take place, the labor, materials, and equipment necessary to build, and the limitations of and constraints on construction work, is essential. Years of hands-on construction experience and time on the jobsite witnessing how projects get built benefit the application of this knowledge in practice. As a result, those with extensive construction knowledge and experience, namely construction professionals, are extremely valuable to any efforts carried out to improve constructability on a project.

Addressing constructability on projects may be undertaken informally or through a formalized process to improve constructability. The nature and format of the constructability process employed is often dependent on the type of project and contracting environment. Most importantly, though, addressing constructability early in the project provides opportunities to influence cost and quality that diminish with the passage of time over the life of the project.

Constructability programs may come at a cost to a project. The cost, however, is typically outweighed by the potential benefits. In addition to ease of construction

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and quality documents, the benefits of a high level of constructability can include: reduced construction cost, less re-work of construction put in place, shorter construction schedules, improved construction site safety, and other positive project outcomes.

While the benefits are recognized, barriers to addressing constructability exist that often prevent its optimization on projects. A lack of construction experience in the design team and the absence of tools to assist designers in addressing constructability limit the extent to which design professionals can impact constructability. Getting the construction knowledge incorporated when needed early on in the project during planning and design is often difficult when competitive bidding requirements govern the project. When a formal constructability process exists within an organization, the lack of a champion to oversee the process can limit its effectiveness. Overcoming these and other barriers requires planning on the part of the owner and project team. With appropriate consideration and mitigation of the barriers, the potential benefits of improved constructability can be realized.

The importance of constructability to project success and the potential benefits have motivated the construction industry to understand and enhance constructability on projects. This special publication on constructability has been developed to assist the construction industry in these efforts. The publication provides a resource of information on current constructability knowledge and practice. It is intended to act as a resource for the construction industry to learn about constructability and help improve the level of constructability in practice. It documents current knowledge on constructability as well as the state of practice in the construction industry, and discusses the issues of cost, benefits, contractor input, and constructability processes as mentioned above.

The publication is aimed at a broad audience consisting of construction industry professionals, specifically designers and constructors, and engineering and construction academics. Individuals in design, construction, and owner organizations will find this publication beneficial when addressing constructability on future projects. In addition to providing a resource of constructability knowledge, the publication is intended to stimulate the academic community and construction industry to further explore constructability and take action to improve it on future construction projects.

The publication contains eight peer-reviewed papers authored by industry practitioners and academicians who are knowledgeable about constructability and the construction industry. Each paper focuses on a different constructability topic. Introductory papers provide background knowledge on constructability, how it is defined and characterized, and the current state of practice. Subsequent papers cover a variety of different topics including: constructability programs that have been developed and implemented in practice; keys to the implementation of constructability programs; design tools that are available to assist design professionals in addressing constructability on projects; and the benefits and costs associated with addressing constructability on a project. The final paper provides a look forward at where constructability research and practice are, and should be, headed based on the papers and topics discussed in the publication. The papers are organized into various sections as described below.

The Concept of Constructability

The publication begins with two papers that introduce the concept of constructability, in theory and practice, and provide a summary of previous research and what is known about the topic. From the initial discussions in the early 1970s, the concept of constructability has attracted many researchers and practitioners. Constructability research over the past several decades has examined many different aspects of constructability in theory and in application. The first paper in the publication, titled "Constructability Review Process – A Summary of Literature", by Sathyanarayanan Rajendran, reviews and summarizes literature on constructability. The paper includes a brief history of constructability followed by a detailed discussion on the recommended best practices for the creation, implementation, and evaluation of constructability processes. The paper is intended to be a reference guide for understanding the current level of knowledge in the industry.

In the second paper in this section, titled "Constructability as a Project Lifecycle Property", John Gambatese and Phillip Dunston investigate constructability as a lifecycle property similar to operability and maintainability. The paper describes a study to investigate the importance of constructability compared to other lifecycle properties and project objectives from the owner, designer, and constructor perspectives. Additional evidence of how and when constructability is addressed on projects is presented.

The Constructability Committee within the ASCE Construction Institute has also investigated the current state of practice of constructability in the construction industry [Pocock, J.B., Kuennen, S.T., Gambatese, J., and Rauschkolb, J. (2006). "Constructability State of Practice Report." *Journal of Construction Engineering and Management*, ASCE, 132(4), 373-383]. This comprehensive study surveyed the construction industry to understand the nature and extent to which the construction industry currently addresses constructability on projects. The published paper outlines the "how, when, where, and why" of constructability in current practice. Recommendations are provided that identify what the construction industry needs to do to improve the constructability of its projects. Readers are encouraged to review this paper as well.

Constructability in Practice

This section of the publication explores how constructability is addressed in practice within different environments. In their paper titled "Constructability Issues and Review Processes", Donn Hancher and Paul Goodrum describe the results of a study that examined how to implement a constructability process on projects for state transportation agencies. The paper summarizes different approaches for conducting constructability reviews, the barriers to their success, and the process that is currently being adopted by a state transportation agency, the Kentucky Transportation Cabinet.

Recording lessons learned from past projects is an important part of maintaining and increasing the level of knowledge in an organization. This is especially true with respect to constructability given that much of the knowledge is experience-based and contracting arrangements often make it difficult to transfer the lessons learned from those knowledgeable (construction personnel) to those who implement the knowledge (design professionals). The paper titled "Effective Enterprise-wide use of Lessons Learned – Specific Experience in the Project Design Environment" by Jeffrey Kirby and Bill East identifies the contents of and requirements for an effective lessons learned business process. A software program that enables this process to occur is described, and the costs and benefits of such a lessons learned approach are identified.

In her paper titled "Using Transportation Construction Contracts to Create Social Equity", Sarah Picker approaches constructability from a different perspective, that of driving social change within transportation contracts. The paper contemplates the construction contract as a specific mechanism to achieve policy which, inevitably, involves owners, designers, and contractors/constructors. Marketing and community planning efforts that the owner and constructor can implement are discussed, the outcome of the efforts ultimately being reflected in more bidders meeting contract Disadvantaged Business Enterprise (DBE) goals.

Constructability Tools and Technologies

One of the obstacles to addressing constructability on projects that has been identified is a lack of tools to assist design professionals and those conducting constructability reviews. The need for constructability tools and resources is evident in the fact that those designing projects often do not have the requisite construction knowledge, and conducting a comprehensive constructability review on a project is often a daunting task given the large sets of plans and specifications on some projects. Visualizing the construction process from two-dimensional drawings can also be difficult, even for experienced constructors. New technologies that locate errors and omissions, highlight interferences, and allow for time-lapsed viewing of the construction sequence can greatly benefit the ability to improve constructability. Research and development of such tools are needed.

The first paper on this topic, titled "An Overview of Constructability Tools" by Deborah Fisher, provides an overview of 27 different constructability tools. The tools can be used for implementing a constructability process or analyzing the level of constructability on any project. Fisher addresses three categories of tools: policy/process-based tools, modeling tools, and technology-based tools. The technology-based tools include both graphical (CAD animation) and non-graphical (databases, analytical) computer models. All of these tools are then mapped onto a generic constructability planning process model for a typical project so that users can develop an implementation strategy with these tools.

Eul-Bum Lee and Nadarajah Sivaneswaran authored the second paper in this section, titled "CA4PRS: A Constructability Analysis Tool for Urban Highway Rehabilitation Projects". This paper profiles a specialized constructability software program developed for pavement rehabilitation projects. The paper provides validation of the software as it was applied to several real projects and successfully predicted production performance. The software is a promising example of other constructability analysis and prediction tools we hope to see for many other applications.

Constructability Impacts, Barriers, and Limitations

Identification and knowledge of the barriers and limitations to addressing and improving constructability are needed in order to make strides to enhance it on projects. In addition, understanding the impacts, both positive and negative, of the level of constructability on a project can be instrumental in motivating project team members to improve it. One paper addresses these issues. The paper, written by Phillip Dunston, John Gambatese, and James McManus and titled “A Cost and Benefit Model for Constructability Review Implementation”, describes an effort to quantitatively assess the success of a constructability review process on individual projects and throughout a capital improvement program. A model is presented for quantitatively comparing the benefits and costs associated with the formal implementation of constructability reviews in a state transportation agency. The benefit/cost model developed is founded on the proposition that constructability reviews provide efficiencies that result in significant reductions in costs and schedule for planning, design, and construction. The authors suggest that valid comparison between the benefits and costs and action to affect the outcome will ultimately lead to projects that are highly biddable, buildable, and maintainable.

The previously published “Constructability State of Practice Report” described above also provides the construction industry’s perception of the obstacles that inhibit constructability. These include: lack of open communications between designers and constructors; inadequate construction experience; difficulty coordinating disciplines; lack of resources; and project delivery methods (e.g. Design-Bid-Build). Owners are a key aspect of overcoming these barriers.

Conclusion

Despite the considerable progress that has been made in recent years in improving constructability, the impact that poor constructability has on the diminished success of projects remains significant. There is still much to be done at both the project level and program-wide to improve constructability at the work face, especially on small and medium-sized projects where resources may not be as plentiful. However, we have learned through research and experience that there is much to be gained by looking holistically at the construction process and better integrating construction and design knowledge.

Drawing on the insights of the authors in each of the papers, the publication concludes with a commentary, titled “The Way Forward: Recommendations for Future Constructability Research and Practice”, that presents a roadmap for future constructability research and practice. The barriers to increased collaboration and the integration of construction knowledge in design are not trivial, and the progress of constructability efforts is likely to be evolutionary. We hope that this publication and its contributors will offer a step forward on that path.

Constructability Review Process – A Summary of Literature

Sathyanarayanan Rajendran[4]

Abstract

Constructability has been defined as the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives. Application of constructability concepts and principles during the project life cycle can make the delivery of a facility easier, safer, and cheaper. The concept of constructability in the construction industry surfaced in the 1970s, attracting many researchers and practitioners. As a result, research has been conducted on this topic over the past three decades. The purpose of this paper is to review and summarize the constructability literature that has been added during that time. For this purpose, "information" was gathered from available sources of relevant material, including journals and reports, whether paper-based or in electronic format. Discussions in this paper include a brief history of constructability followed by a detailed discussion on the recommended best practices for the creation, implementation, and evaluation of constructability programs in the construction industry. This paper is intended to be a reference guide for researchers and practicing engineers to increase their understanding of constructability.

Introduction

Constructability is a project property which has attracted the attention of many industrial and academic organizations in the past three decades. The concept of "constructability" in the United States, or "buildability" in the United Kingdom, emerged in the late 1970s. This emergence, according to studies of the British and American industries at that time, was an effort to stop the declining cost-effectiveness and quality in the construction industry (Emmerson 1962; Business Roundtable 1982, 1983 as cited in Uhlik and Lores 1998). These studies found that lack of integration between construction and design was the root cause for the cost and quality issues faced by the construction industry. In one of the early papers published on the topic (Paulson 1976 as cited in Uhlik and Lores 1998), Paulson discussed the importance of inserting construction knowledge into design. In his paper, Paulson explained how

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decisions made in the early phase of a project could highly influence the cost and quality of construction. This process of inserting construction knowledge in the design was called "constructability" and has been the topic of research ever since. A number of studies have been conducted in this area and numerous researchers have made important recommendations. Today, constructability processes are being widely applied in the construction industry and have become an integral part of the project development process.

The purpose of this paper is to provide a summary of the literature on constructability research. This paper can serve as a reference document for current and prospective constructability researchers and industry practitioners. An extensive review of the literature accounted for constructability publications over the past 30 years that appeared in textbooks, journals, and reports. The literature presented in the paper has been classified under two major industry divisions that adopt constructability concepts: industrial/building and transportation. Areas covered under these two divisions include:

- Constructability definitions,
- Constructability program benefits,
- Constructability concepts, and
- Recommended best practices for the creation, implementation, and evaluation of constructability programs.

Constructability research in the transportation industry has been minimal compared to that in the building industry. Hence, most of the discussion and most of the studies referenced in this paper are related to the building industry. An exhaustive discussion of each of these areas is not provided in this paper considering the amount of literature added in the past 30 years. Readers are referred to the cited references for an in-depth discussion on the subject.

Constructability Definitions

The reader's understanding of the term "constructability" is essential for understanding the research undertaken. The Construction Industry Institute (CII) defined constructability as the "optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieve overall project objectives" (CII 1986). Reflecting on the fact that constructability is a project property similar to operability and maintainability, and that there is a continuum in the level of constructability rather than just "optimum", constructability has also been defined as a project property that "reflects the ease with which a project can be built and the quality of its construction documents" (Dunston et al. 2003).

Various other definitions have emerged based on the individual project needs and the type of project. Literature suggests that constructability can be defined as:

- "the capability of being constructed" (ASCE 1991);
- "a measure of the ease or expediency with which a facility can be constructed" (Hugo et al. 1990);

- "the integration of construction knowledge, resources, technology and experience into the engineering and design of a project"(Anderson et al. 1995); and
- "a process that utilizes construction personnel with extensive construction knowledge early in the design stages of projects to ensure that the projects are buildable, while also being cost-effective, biddable, and maintainable" (AASHTO 2000).

Importance of Constructability (Benefits)

One of the major incentives to improving constructability is the potential significant benefit associated with a high level of constructability. Cost savings is one recognized benefit. In the construction industry, profit plays a decisive role in staying in business. Each firm tries to identify a new strategic advantage that will help improve their profit margin to stay competitive. Constructability is one such strategic advantage that industry practitioners can use to realize cost savings. This section of the paper presents research that has focused on the benefits of implementing a constructability program in building and transportation projects.

Industrial and Building Projects. The Business Roundtable (BRT) provided early reports on the benefits of a high level of constructability. BRT estimated that constructability improvements saved at least 10-20 times the cost of the constructability effort (Business Roundtable 1982). It is common that when we talk about benefit, we think of the cost savings as the only benefit. However, there are several other benefits in addition to cost savings. Constructability benefits can be classified as qualitative and quantitative. Qualitative benefits include: improved problem avoidance, improved safety, reduced amount of rework, better communication, increased commitment from team member, and much more. The quantitative benefits include: reduced engineering cost, shorter schedule duration, and reduced construction cost (Russell et al. 1994a).

Beyond the documented quantitative benefits from improving constructability, the qualitative benefits in and of themselves are substantial. Documented benefits, not reflecting these qualitative benefits, will usually be underestimated (Russell et al. 1994a). The conclusion made by Russell et al (1994a) was reinforced by Griffith and Sidwell (1997) who reported that constructability implementation benefits may be manifest, others more obscure, some quantitative in nature, while others are more subjective. Benefits can also be quite pragmatic, measurable not only in terms of cost, time, and quality, but in terms of the physiological and psychological gains for the building team members. The benefits of improving constructability have become well recognized and may extend across the total building process, and include the following: better conceptual planning; more effective procurement; improved design; better construction methods; more accomplished site management; more effective team work; higher job satisfaction; increased project performance; and enhanced recognition.

Quantifiable benefits from early implementation of constructability programs have been documented on projects in the industrial and building construction industries. Russell et al. (1994b) studied four cases of construction projects, of which three tracked costs associated with constructability implementation and maintained a log of constructability suggestions. This data provided adequate information to determine a benefit/cost ratio. These projects obtained a 10:1 benefit/cost ratio. Some of the qualitative benefits that were not accounted for in the ratio included: enhanced construction sequencing, procurement strategies, and enhanced project coordination (Russell et al. 1994b). While Russell at al. report that improving constructability has benefits from early implementation, Eldin (1988) reported a case study where cost and time savings were realized even though the constructability improvement program was implemented a few months after the start of the construction phase.

In another study, Russell and Gugel (1993) compared the annual documented savings attributable to improved constructability for the constructor- and owner-performed constructability programs. The study included both on-going and completed projects. For the constructor-performed program, benefit/cost ratios of 24.3:1 for all projects and 21:1 for completed projects were realized. Within the owner-performed program, an average benefit/cost ratio of 16:1 was realized for completed capital projects. Differences in average benefit/cost ratios reported between the two programs were attributed to the significant cost required to operate and maintain the owner's program relative to the constructor, as well as the types, size, similarities, and labor-intensity of the facilities constructed. Based upon the costs and benefits presented in the study, the construction industry as a whole can benefit from optimizing the construction process through timely input of construction knowledge and experience (Russell and Gugel 1993).

Implementing constructability programs not only provides benefits to owners and contractors, it can also benefit designers. Arditi et al. (2002) reported the benefits of constructability among design firms. The most significant benefits include developing better relationships with clients and contractors, being involved in fewer lawsuits, and building a good reputation.

Transportation Projects. Studies discussed above indicate that, when methodically implemented, front-end constructability improvement efforts are investments that result in substantial return to all three groups—owner, designer, and contractor in the industrial and building industry. The fact that similar, favorable benefits can be achieved on transportation projects needs proper recognition, documentation, and acknowledgment. Anderson and Fisher (1997) state that although constructability efforts require up-front investment of resources, in the long run very attractive benefits accrue. This has been proven by research studies and pilot projects in the transportation industry.

A study performed for the National Cooperative Highway Research Program (NCHRP) by the Arizona Department of Transportation Constructability Engineer provided evidence of the potential benefits. In a set of six projects selected from 35 that were reviewed for constructability, the savings achieved as a result of constructability improvements amounted to 1.7% of the total cost of the six projects (about \$68,000,000), or \$1,200,000. This translated into a benefit/cost ratio of 25:1;

that is, $25 was saved in project cost for every dollar spent on constructability analysis (Anderson and Fisher 1997 as cited in Anderson et al. 1999).

In another study conducted by Dunston et al. (2003), the authors examined two transportation projects to quantify the costs and benefits of implementing a constructability review program. The study reported benefit/cost ratios of 2.29 and 2.10 for the two projects. Several State Highway Agencies have started to formalize constructability review processes, which is a direct result of the documented benefits reported in this section.

Constructability Concepts

Constructability concepts referenced and/or listed in this section include some of the important concepts identified by researchers and those that are being used in different countries.

The Construction Industry Institute (CII) formed a Constructability Task Force to determine principles/concepts that could be used to improve constructability in each phase of a project: (1) conceptual planning, (2) design and procurement, and (3) field operations. The Task Force conducted three major studies for this purpose (CII 1986a; 1986b; 1988). In the first study (CII 1986a), CII sought to determine approaches that will aid constructability improvement during the conceptual planning phase of a project. Three aspects were identified as being important: developing a thorough project plan; detailing site layout; and considering alternative principal construction methods.

The second study (CII 1986b) examined how construction knowledge and experience may be most effectively utilized during the engineering and procurement phases of projects. The conclusions were:

- design and procurement should be construction driven;
- designs should be configured to enable efficient construction;
- designs should be scoped to facilitate fabrication, transport, and installation;
- designs should promote utilization of resources;
- designs should assist construction under adverse weather conditions; and
- specifications should serve to simplify the construction operations.

CII also explored how construction knowledge and experience can enhance constructability during field operations (CII 1988). The major finding from this study was that, "Constructability is enhanced when innovative construction methods are utilized." This study resulted in CII's 14 constructability concepts (six considerations during conceptual planning, seven for consideration during the design, engineering, and procurement stages, and one concept for consideration during site operations), which were later appended with three additional concepts (CII 1992).

Researchers from other countries have also made similar efforts to develop constructability concepts. The Construction Industry Research Information Association (CIRIA) of the United Kingdom provided seven "Guidelines for Buildability" which were later expanded into 16 "Design Principles" for practical buildability (CIRIA 1983 and Adams 1989 as cited in Trigunarsyah 2004). Fox and Cockerham (2002) proposed guidelines for successful application of constructability rules/concepts to bespoke buildings in the United Kingdom. Bespoke buildings are those designed to fulfill the requirements of one particular client and/or a single specific location. The researchers reviewed the Design for Manufacture and Assembly (DFMA) rules and existing building designs as a potential source of constructability rules. Based on their research, they recommended four guidelines for the successful application of constructability rules to bespoke buildings:

1. Focus rules on each design stage in sequence;
2. Support rules with self-explanatory strategies and production databases;
3. Develop routine and foolproof application methods or rules; and
4. Target rules on best available productivity/quality improvement opportunities.

In Australia, the Construction Industry Institute Australia (CIIA) has developed 12 principles of constructability based on the CII constructability concepts, which were tailored to the Australian construction industry (CIIA 1993 as cited in Trigunarsyah 2004).

In Malaysia, Nima et al. (2002), reported 23 constructability concepts for the purpose of their study based on the previous constructability studies. The 23 constructability concepts were distributed as: seven considerations during conceptual planning, eight for consideration during the design, engineering, and procurement stages, and eight concepts for consideration during field operations.

Constructability Implementation

Constructability implementation is a great challenge to the practitioners since it requires putting all of the essential concepts identified into a workable package. Successful implementation of a constructability program depends on the understanding of some basic essential elements of the program. This includes:

- When a constructability review process should be started in the project life-cycle;
- Who should be part of the constructability team;
- What should be the main focus of a constructability program; and
- How to implement a constructability program.

The Construction Management Committee of the American Society of Civil Engineers (ASCE 1991) states that, for any project to maximize its savings in terms of time, cost, and quality, the construction input or constructability, has to be started during the conceptual planning stage and continue during the entire life of the project. The ability to influence cost is high during this stage and reduces as the project reaches the start-up stage.

The constructability team should constitute personnel from different fields with varied expertise. Experienced construction personnel need to be involved with the project from the earliest stages to ensure that the construction focus and experience can properly influence owners, planners, and designers, as well as material suppliers. The construction personnel should come from the staff of the owner, a separate construction management firm, or possibly the designer or constructor (ASCE 1991). The construction person should be a full-fledged member of the project team, with access to, and participation in, the early decisions that affect the project. In certain cases a full-time manager should be recruited to manage constructability reviews. Individuals managing constructability reviews should be knowledgeable engineers, must have the background of construction experience, be able to speak with authority, and have the team and people skills required to clearly put forth their ideas without alienating the rest of the team. In addition, to broaden the constructability focus, specialists should be brought in to look at specific tasks (transportation, structural, welding, rigging, piping, coatings, instrumentation, etc.) during the project development process (ASCE 1991).

A constructability program should focus on several important issues for its success. A typical constructability program should contain factors, such as project delivery, project management, contracting strategy, etc., that would reduce the overall project schedule, improve overall project quality, operability, maintainability, and reliability, and the overall life-cycle cost (ASCE 1991). Readers are encouraged to refer to the original document for the entire list.

Implementation of constructability reviews is a crucial part of a constructability program. A great program may be developed on paper, but if it is not implemented properly, it will not yield the benefits. Questions that immediately arise when talking about implementation include:

- What types of constructability programs can a company adopt?
- Who should support the program within the company?
- What are the key components of a constructability program?
- What tools are available for implementing constructability programs?
- How formalized should these programs be?
- What are the barriers for its effective implementation?
- How to assess the existing programs and make improvements?

The following sections aim to provide the readers with a basic understanding of the implementation process by answering these questions.

Constructability Programs

ASCE (1991) defines a constructability program as "the application of a disciplined, systematic optimization of the construction-related aspects of a project during the planning, design, procurement, construction, test, and start-up phases by knowledgeable, experienced construction personnel who are part of a project team." A useful tool in the constructability program implementation process is the constructability implementation roadmap developed by CII (CII 1993). The roadmap offers guidance in the planning, development, and implementation of a constructability program, and is intended to be used by owners, designers, and contractors. The constructability implementation roadmap provides an overview of the constructability process by emphasizing six milestones:

1. Commit to Implementing Constructability
2. Establish Corporate Constructability Program
3. Obtain Constructability Capabilities
4. Plan Constructability Implementation
5. Implement Constructability
6. Update Corporate Program

Owners or contractors can choose to implement constructability programs at the corporate (company) level and/or the project level depending on several factors. These factors include: commitment and support from top management, budget, resources, etc. CII (1987) documents the ideas, steps, and procedures that have worked best in implementing constructability programs at both the corporate and project levels. Important elements of both of these types of programs are discussed below.

Company Level Program. Large companies that realize the benefits of a high level of constructability and possess sufficient resources may choose to implement a corporate level constructability program. In order to develop a successful company-level constructability program, a company should consider the following steps: self-assessment; corporate policy; organization and procedures; executive sponsor; constructability database; training; and appraisal. Companies should start by assessing where they are with regards to constructability. When developing a company policy statement which outlines its goals and commitments to achieve a high level of constructability, the company should follow it. An individual who holds a top position in the company should be appointed as the executive sponsor for the program. His/her responsibilities toward the program should include: financial support, timely and effective supervision, and management of the program's continuous operation. The program implementation procedure should be clearly outlined by the company and made available to the responsible players. On successful implementation of these steps, a thorough and periodic appraisal of the program is required. Any shortcomings should be addressed with improvements immediately. The report also suggests the maintenance of a corporate "lessons learned" database through the appointment of a database custodian (CII 1987).

Project Level Program. Project level programs can be a result of two situations. One, a company will have an in-place corporate program and will address constructability on each of its projects. The other case would be a contractor who does not have a corporate program in place but is required by the owner to have a project level constructability program as part of the contract. These contractors might find this program guideline to be a useful tool to implement constructability at the project level. In either case, the project owner has a significant role in the implementation of a project-level constructability program. The project manager should issue a simple policy statement on behalf of the owner that outlines the program goals and the owner's commitment to constructability. The use of multi-party (designer, builder, and owner) constructability teams is essential in project-level constructability programs. An organization chart should be published which reflects the constructability participants and their roles (CII 1987).

The Project Manager, assisted by the Senior Project Engineer, Senior Construction Representative, and Project Constructability Coordinator, should conduct constructability training at the project level. Integration of constructability specialists into the planning and design process from day one is critical in the success of the program. Constructability program implementation procedure documents should be brief and allow maximum flexibility in their execution. Once the project-level program has been implemented, it is recommended to quantify major savings where there is a clear indication of savings. The heart of the appraisal should be a subjective evaluation reported periodically by the project manager to the executive sponsor together with his/her current estimate of major savings from improved constructability. This practice is especially important for contractors implementing constructability programs for just a single project as it will help the construction firm's top management realize that constructability is a profit center and prompt them to develop a corporate-level program. The project constructability coordinator or others in charge holds the responsibility to prepare "lessons learned" for the project manager on an ongoing basis. The lessons should be forwarded to the database custodian for inclusion in the corporate "lessons learned" data file (CII 1987).

Radtke and Russell (1993) developed a tool for implementing a project level constructability program. The tool consisted of a process model to aid owners in the implementation of constructability programs at the project level. The model is based on the data obtained from the CII Constructability Implementation Task Force (1989) and various constructability implementation programs that were used in the industry during the time of the study. The researchers cite eight approaches from Radtke (1992) to implement constructability programs ranging from construction management practices to constructability services and programs for comprehensive constructability tracking. Out of these eight approaches the model process was created from the strengths of primarily three approaches:

1. constructability contract documents – provided insight on how to secure constructability input form other project participants;
2. specialized formal constructability programs – provided example constructability procedures, team organization, and cost-benefit analysis that were project specific; and
3. comprehensive constructability tracking – provided example means to document savings and lessons learned over several projects.

The model consists of milestones, steps, and activities. Three milestones are described as: (1) obtaining constructability capabilities; (2) planning constructability implementation; and (3) implementing constructability. Within each milestone specific steps are described, and each step is further described by activities. The model process provides a benchmark for owners to use on their projects for the purpose of enhancing the constructability on their projects and in turn gaining the maximum benefits from the constructability improvement program (Radtke and Russell 1993).

Constructability Approach Selection

Constructability programs can be implemented in varying degrees of formality. Informal constructability approaches, usually indistinguishable from other construction management activities, may include design reviews and construction coordinators. Formal programs, usually having a documented corporate philosophy and budgeted resources, may involve tracking of lessons learned on past projects, team-building exercises, and construction personnel participating in project planning. A formal constructability approach may yield greater benefits than informal approaches (Russell et al. 1994b). The decision on what approach to implement, depends on several factors including the owner and project characteristics.

A tool such as the constructability approach selection model developed by Gugel and Russell (1994) assists owners in efficiently determining the appropriate means by which to incorporate construction knowledge and experience into the designs of their projects. The model consists of three approaches to implement a constructability program: one informal and two formal (formal project level and comprehensive tracking). The model consists of a hierarchy of decision levels. Within these levels, there exists three steps: (1) individual assessment of owner and project characteristics resulting in a single conclusion of a formal or informal approach; (2) combining owner and project characteristics into a single conclusion of an informal or formal approach; and (3) if a formal approach is concluded, a decision is needed as to whether it is formal project level or comprehensive tracking. To assess the above-mentioned owner and project characteristics, a framework of variables described by parameters was also developed by Gugel and Russell (1994).

Constructability Implementation in Transportation Projects

Although constructability has been studied in the transportation industry, its exposure has not been as widespread as in the industrial and building construction industries. A limited amount of research has been conducted by the transportation industry in the area of constructability. One of the early studies was initiated by the Texas Department of Transportation (Hugo et al. 1990 as cited in Anderson 2000). As part of the study a guide was developed that describes constructability in some detail with respect to its definition, its relationship to other programs such as value engineering, why and when to pursue constructability improvement efforts, and factors affecting highway constructability. The guide offers a constructability enhancement program. Some of the other Departments of Transportation that have conducted constructability research include: Florida Department of Transportation (FDOT) (Ellis et al. 1992); Arizona Department of Transportation (ADOT) (Wright 1994); Wisconsin Department of Transportation (WDOT) (Russell and Swiggum 1994); and Kentucky Transportation Cabinet (Hancher et al. 2003).

The National Cooperative Highway Research Program (NCHRP) initiated a research project to develop a constructability review process (CRP) for transportation facilities (NCHRP 1997). This research identified the need for contract documents to ensure rational bids and minimize problems during construction. State transportation agencies (STAs) recognized that a significant aspect of developing high-quality contract documents is to incorporate a review process in project planning and design to assess a project's constructability. This process must include input from professionals involved in planning, design, construction, operation, and maintenance of transportation facilities (NCHRP 1997). The basic objective of the study was to develop a systematic approach and methodology for a constructability review process. The methodology must incorporate constructability concepts, existing analytical tools to support constructability reviews, and functions needed to apply both concepts and tools. Also, the methodology must be designed to fit different project characteristics and requirements. Finally, it must be adaptable to different state transportation agency approaches to project development (Hancher et al. 2003).

The major product of the study was the "Constructability Review Process (CRP) for Transportation Facilities-Workbook (NCHRP 1997a). The CRP workbook begins with an overview, primarily for senior policy makers, that explains the why's, what's, and how's of the CRP. Implementation guidelines, which constitute the major portion of the workbook, describe in detail each constructability function and its steps, actions, and tools. Issues affecting how a step and action are carried out are identified. Finally, outcomes of each function are illustrated using two actual project applications that are integrated throughout the guidelines. In addition the workbook presents a glossary of terms, complete descriptions of tools, and suggested future tools. Readers associated with the transportation industry will find this document to be a useful reference.

Another study that contributed understanding of how to implement constructability review processes in the transportation industry was the "Constructability Review Best Practices Guide" developed by the American Association of State Highway and Transportation Officials (AASHTO) (AASHTO 2000). The guide was developed to assist AASHTO member state agencies in developing a constructability review process that will meet the needs of the agency. The guide describes the elements that are a part of the successful constructability practices that were employed by state transportation agencies during the study (AASHTO 2000). It also highlights the constructability programs implemented by the state transportation agencies that participated in the study. Key elements for successful CRPs are outlined and different tools used to implement these CRPs are presented in the guide.

Constructability Implementation Barriers

Constructability barriers can be defined as any significant inhibitor that prevents effective implementation of the constructability program (O'Connor and Miller 1994). Constructability barriers are evident in almost all organizations at both corporate and project levels. A constructability program can be efficient only when these barriers are identified and controlled effectively.

According to O'Connor and Miller (1995), treatment of constructability barriers should involve a three-phase cycle of identification, mitigation, and review.

Initial efforts in barrier control should focus on determining the presence and severity of such barriers identified. The severity of these barriers varies widely from company to company, particularly with respect to constructability program ranking, organization type, project type, and annual volume of work (O'Connor and Miller 1994). Once these barriers have been identified they can be controlled with the help of barrier breakers. Such breakers should be both effective in combating the barriers and should be implementable or easy to apply. O'Connor and Miller (1995) identified several such barriers and proposed different barrier breakers to control these barriers. Readers are referred to O'Connor and Miller (1995) for a complete list of the barriers and the barrier breakers.

Another research study that examined the barriers to improving constructability was conducted by Jergeas and Van der Put (2001). They reported several gaps between the potential benefits of applying constructability principles and those benefits actually realized in practice. These gaps are in the following areas:

- Up-front involvement of construction personnel;
- Achieving efficiency in the construction effort; and
- Use of informative construction methods and advanced technology.

The principal barriers that contribute to these gaps are presented briefly below.

- *Up-front involvement of construction personnel*: The barriers include: lack of mutual trust, respect, and credibility between project planners, designers, and the constructors; traditional contracting practices; and lack of desire and commitment by the owners to commit funds and resources.
- *Achieving efficiency in the construction effort*: Some of the barriers identified under this area are: congestion around construction sites, especially sites within or adjacent existing operating facilities; rigid specifications that limit design flexibility and are prepared by designers who often lack practical field experience; and lack of communication between designers and constructors who often seem to be working at cross-purposes.
- *Use of informative construction methods and advanced technology*: Risk aversion, lack of trust by owners, cost of advanced computers, and time required to train people are some of the barriers reported by the authors in this area. Readers are encouraged to refer to Jergeas and Van der Put (2001) for a detailed list of these barriers.

Griffith and Sidwell (1997) note that the fragmented nature of building and the segregated roles of the project team, characteristic in traditional building procurement, present inherent and significant barriers to the widespread adoption and developing success of constructability programs. Moreover, support is stifled by the obstacles to innovation in design, technology, and management, brought about through: the low level of awareness; demarcation; the lack of incentives; reticence; and the competitive stance adopted by construction professionals. Such difficulties and the barriers they create to the further development and application of constructability concepts are complex and involved and will not be overcome easily (Griffith and Sidwell 1997).

Barriers Faced by General Contractors and Designers

Two different studies reported the barriers of constructability from a general contractor's and a designer's perspective (Uhlik and Lores 1998; Arditi et al. 2002). One of the major goals of the study by Uhlik and Lores (1998) was to detect the prevalence of common barriers to improving constructability as perceived by general contractors. They found that general contractors had a common opinion on the topic of barriers regardless of the type of work, volume of work, or arrangement of contract used. The most common barriers identified by general contractors were that design without construction input is the traditional form of contracting and that designers lack construction experience and knowledge of construction technologies. Recurring barriers identified by the authors were the limitation of lump-sum competitive contracting and the adversarial attitude between designers and contractors. A new barrier to constructability was found to be designers' reluctance to include contractors in constructability review for fear of marring their reputation.

Arditi et al. (2002) reported that faulty, ambiguous, or defective working drawings, incomplete specifications, and adversarial relationships were found to be the three major factors that cause constructability problems among design firms. On the other hand, owner resistance and budget limitations are perceived by designers as having a trivial effect on constructability. This finding does not agree with the generally held belief that owners are usually reluctant to allow their designers to conduct formal constructability programs because of the highly visible extra cost to their projects.

The literature reveals that there are several critical issues or barriers in the transportation industry that impact constructability implementation. In a survey conducted by Anderson et al. (1999), constructability issues faced by state highway agencies, design firms, and construction contractors, were recorded. These issues are categorized into those relevant to project execution processes, project planning and technical design documents, and project resources. Analysis and interpretation of the issues within these three categories suggest eleven paradigm shifts that the state transportation agency management must address to successfully implement a constructability program (Anderson et al. 1999).

Lastly, Goodrum et al. (2003) reviewed the constructability barriers and issues in highway construction. The authors examined the common barriers such as the availability of time and manpower. They also identified some of the most common constructability issues that arise on highway construction projects, such as utilities, right-of-way commitments, and traffic control.

Assessment of Constructability Programs

Constructability programs should be continually assessed for performance. Performance evaluation and feedback from designers, contractors, and other field personnel will help improve the program. Assessment of constructability can be within an organization, an industry, or a profession. What is the status of constructability within a company? What is the status of constructability in the construction industry? What is the status of constructability among state highway agencies? Assessments can be established to answer these questions. The following is a summary of literature that describes efforts to answer these questions.

O'Connor and Miller (1994a) recommend that organizations use a Constructability Program Evaluation Matrix to make continuous improvements to their programs. The primary goal of constructability self-assessment is to obtain an objective evaluation of constructability efforts. The results of a constructability program self-assessment can be invaluable for: setting and clarifying realistic constructability program objectives; identifying current program benefits, and identifying needs for program improvements.

The Constructability Program Evaluation Matrix was developed based on 15 significant corporate and project parameters required for effective constructability implementation. It provides a method for evaluating the maturity level for each parameter at both the corporate and project levels. This tool was developed with characteristics from constructability programs successfully implemented in the construction industry. It allows management to determine the level of the program in its organizations and, if necessary, to improve the program. A five level classification system was used by O'Connor and Miller (1994a) which allows for efficient differentiation, categorization, and description of efforts, and smooth transformation of the parameters identified into a tool for program assessment. This system also proves useful for program benchmarking, and for identity and comparison of constructability program elements and efforts. The evaluation process also includes the barrier identification and control discussed in the previous section.

O'Connor and Miller (1994a) reported that the constructability programs of EPC (Engineer-Procure-Construct) firms, large-volume firms, and those involved in industrial projects tend to be more developed, while the constructability programs of general contractors, construction managers, designers, owners, small-volume firms, and those involved in either the general building or utility sectors tend to be less developed.

O'Connor and Miller's (1994a) conclusion that there was a significant lack of formal constructability efforts existing among general contractors initiated another research study by Uhlik and Lores (1998). The intent of this subsequent research was to assess the present constructability practices of general contractors by questioning how the contractors are participating during the preconstruction phase of the project. It was found that a great proportion of general contractors surveyed (90%) did not have a formal constructability programs, nor did they take actions toward the implementation of constructability programs. Companies with larger volumes of work tend to have formal constructability programs, assign constructability coordinators, and include constructability in their contract documents. The authors make several recommendations to improve their involvement in the constructability process: (1) include constructability as a service, (2) make additional efforts to capture lessons learned for future projects to increase efficiency of their organizations, and (3) increase involvement from the Associated General Contractors of American (AGC) and the Associated Builders and Contractors (ABC) to take steps to be more proactive towards constructability and educate their members on constructability implementation and its benefits.

Arditi (2002) reported a more explicit constructability program in design firms than in construction companies, although some design firms perform constructability reviews as part of value engineering or as a component of construction cost management. Almost half of the design firms surveyed by the authors indicated that they have a formalized corporate philosophy about constructability in their organization. The difference between contractors and designers is probably caused by the general belief that constructability analysis is particularly valuable in the design phase (Zimmerman and Hart 1982; Burati et al. 1992 as cited in Arditi 2002).

Assessments on the status of constructability programs among the state highway agencies were also found in the literature (AASHTO 2000). The constructability review survey of state agencies conducted by the AASHTO Subcommittee on Construction in 1999 found that of the 12 states that routinely conduct constructability reviews, only two states (Florida and Georgia) have documented the costs of performing the reviews. The survey also revealed that measuring the benefits of the constructability reviews is generally not performed. A review of the constructability procedures of those state agencies that have written plans reveals that few have developed a methodology for measuring the results of the constructability review process. The Washington State DOT (WSDOT) Manual of Instruction for Implementation of the Constructability Review Process contains a section on the monitoring of constructability review results. The WSDOT procedure sets performance goals in the areas of contract addenda, contract change orders, advertising delays, scope change, construction schedule change and project budget. Since, the last assessment of state highway agencies was made five years ago, some changes can be expected on the findings reported above.

Summary and Conclusions

The purpose of this paper was to provide a summary of the literature on constructability research. An extensive body of literature exists on the topic of constructability in both the building and transportation industries. In this paper, discussions mainly focus on the definitions, concepts, benefits, implementation, and assessment of constructability programs.

A variety of definitions of constructability have been presented. The literature suggests that the most common definition used or cited by the researchers is the CII definition. According to CII, constructability is defined as “the optimum use of construction knowledge and experience in planning, design, procurement, and field operations to achieved overall project objectives”. However more recent definitions stress that constructability is a project property for which a continuum exists and is not necessarily represented by the optimum condition.

A detailed description on the different constructability concepts has been discussed in this paper. Research has been conducted in different countries to develop new concepts. It was found that the concepts are mainly categorized based on three project phases: (1) conceptual planning, (2) design and procurement, and (3) field operations.

One of the most important discussions in the paper is on the importance of implementing constructability programs. The literature suggests and supports the claim that constructability yields substantial benefits in both building and transportation projects. It was found that constructability improvements could save as much as 10-20 times the cost of implementation. It can also be concluded that, in addition to the quantitative benefits, there exists some hidden qualitative benefits such as safety and reduction in rework.

It is evident from the studies summarized in this paper that for any project to maximize its savings in terms of time, cost, and quality, the construction input or constructability has to be started during the conceptual planning stages. A typical constructability program should contain factors that would reduce the overall project schedule, improve overall project quality, operability, maintainability, and reliability, and the overall life cycle cost.

Research has shown that constructability can be implemented at the corporate and/or project level. The constructability implementation roadmap described by CII offers guidance in the planning, development, and implementation of both of these types of constructability programs.

Constructability programs can be implemented using an informal or a formal approach. The constructability approach selection decision model described in this paper will assist owners in efficiently selecting the right approach and determining the appropriate means by which construction knowledge and experience can be incorporated into the design of their projects.

The literature suggests that many constructability barriers exist that can influence implementation of constructability programs. These barriers should be identified and controlled effectively. It is apparent that a constructability program has to be assessed periodically for its performance. The constructability evaluation matrix can be used in assessing the level of development or "maturity" of a constructability program after its implementation. The matrix can be used to make continuous improvements of a company's constructability program.

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Constructability as a Project Lifecycle Property

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Abstract

Constructability is one of many project properties that reflect the characteristics of a construction project. Along with other properties such as operability, maintainability, recommissionability, and decommissionability, constructability is considered in the project development process and can be used as an indicator of success in achieving maximum value from a project. As part of a study of project lifecycle properties, a survey was conducted by the authors to understand the design professional's and constructor's perspective and practice related to constructability. Designers and constructors were asked to indicate: how and when they address constructability; who should address constructability; how important constructability is to project success compared to other properties; and how success in enhancing constructability is measured. The survey revealed that constructability is formally addressed to a great extent by both designers and constructors, and ranked highly compared to other properties for achieving project success. These along with other survey results indicate where in the project's lifecycle constructability is addressed, and how it is addressed. Understanding a designer's and constructor's interests in and influence on constructability can facilitate optimization of the overall value of a facility by the project team.

Introduction

The lifecycle of a construction project is commonly partitioned into separate phases representing different activities and levels of project completeness and use. Each phase, whether it's planning, design, construction, or operation and maintenance, contains unique requirements and exhibits certain traits. Constructability, for example, is a project property that reflects one aspect of project performance in the construction phase. Project success and the overall value of a facility are often evaluated by assessing accomplishment with respect to the various properties and

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comparing the results to stated goals and objectives. The total value or overall performance of a facility is embodied in how fully the project properties are developed and addressed.

A high level of constructability (i.e., clear, concise, and biddable design documents and a design that can be built easily, efficiently, and safely) is a common goal on construction projects. While expressed in the construction phase, constructability is similar to other properties like operability and maintainability in that it is impacted and determined by activities undertaken and decisions made beforehand during planning and design. Project team members act to optimize constructability within their respective scopes of work to plan and design a facility. Success at optimizing constructability depends on many factors. Some of the impacting factors include: the extent to which each party formally considers constructability; the resources available and processes used to address constructability; the construction knowledge of each party; the barriers that prevent each party from impacting constructability; and the priority each party gives to constructability (O'Connor and Miller 1995; Uhlik and Lores 1998; Arditi et al. 2002).

This paper describes a research study undertaken, in part, to evaluate the practices and perspectives of the construction industry related to constructability. The paper specifically focuses on two project team members, the designer and the constructor. The design professional sits in a distinctive position with regards to constructability. By conceiving of and designing the facility's characteristics, a designer plays a central role in establishing the quality and content of the project documents and how easy it is to build the project. The perspective of a designer governs the level of attention that is given to considering and influencing constructability early on in the project lifecycle. Hence, when seeking to optimize a project's constructability, understanding a designer's viewpoint is of interest. The constructor's viewpoint is also of interest. As the project team member immediately impacted by the level of constructability, and as a desired participant in constructability reviews, the constructor can provide firsthand insight into how to best address constructability on a project.

This paper summarizes the results of a survey of design professionals and constructors located in Washington, Nevada, and Oregon regarding project constructability. The survey was conducted as part of a larger research study to establish a better understanding of the lifecycle properties that are currently being addressed and to determine the formal processes that are in place to effectively monitor how these properties are being addressed. Designers and constructors are recognized as playing a central role in establishing a facility's level of performance. Therefore, the designer's and constructor's perspectives on constructability as a lifecycle property are of key importance.

Previous Research and Recommended Practice

Processes for addressing and improving constructability have been developed and studied. To optimize construction cost, schedule, and quality, construction input should begin during the conceptual planning stage and continue during the entire life of the project (ASCE 1991; CII 1986). The ability to influence constructability is higher during early stages of planning and design as decisions regarding the nature and characteristics of the project are initiated. The Construction Management Committee of the American Society of Civil Engineers also suggests the following (ASCE 1991):

- The constructability review team should constitute personnel from different fields with varied expertise.
- The construction personnel conducting the constructability reviews should come from the staff of the owner, a separate construction management firm, or possibly the designer or constructor.
- Construction personnel on the constructability review team should be a full-fledged member of the project team with access to, and participation in, early decisions that affect the project.
- The knowledge and background of the constructability review team members should coincide with the project characteristics and features (e.g., transportation, structural, welding, rigging, piping, coatings, instrumentation, etc.).

The Construction Industry Institute (CII) also provides a view of constructability and the factors that affect constructability on construction projects, and suggests practices for improving project constructability (CII 1986; 1987). This work, along with other research on the topic (O'Connor et al. 1987; O'Connor and Miller 1994; Uhlik and Lores 1998), focuses on the general area of constructability and suggests practices for how engineers can manage and modify a design to facilitate construction.

A recent study of constructability review programs in state departments of transportation resulted in the identification of four keys to constructability: (1) institutionalization of a Constructability Champion; (2) promotion of a quality-driven planning and design process rather than a schedule-driven process; (3) clear guidance on flexibility in implementation; and (4) sensitive handling of contractor involvement (Dunston et al. 2005). This study also revealed the processes used and extent to which the construction industry currently addresses constructability on transportation projects.

The authors previously reported the results of a study to understand the design professional's perspective of constructability in relation to other lifecycle properties (Gambatese and Dunston 2003). Designers were asked to list the lifecycle properties they addressed and rank the importance of each property to the success of a project. Information was solicited with regards to when and how the properties are addressed in practice, and how success in addressing the properties is measured. The survey revealed that constructability is formally addressed more than any other lifecycle property in a project's design. Understanding a designer's interest in and influence on constructability, and similarly the viewpoints of the constructor, can facilitate optimization of the overall value of a facility by the project team.

Research Objectives and Methodology

The assessment of constructability practice and perspectives was part of a larger study to understand the viewpoint held by different project team members regarding project lifecycle properties. Specifically, it was of interest to determine the importance that each project team member places on each property, the means by which each property is addressed, and the techniques used to measure success in addressing each property on a project. A spotlight on constructability was one aspect of this study, and is the focus of this paper.

Given the subjective nature of some of the desired information, a survey approach was used to collect the study data. The researchers developed a survey questionnaire containing questions about constructability and other project lifecycle properties. The questionnaire solicited information regarding the current practice for addressing constructability, priorities given to constructability, and an assessment of industry needs regarding constructability. Six primary topics were covered:

1. Whether constructability was formally considered by the firm
2. The practices used to address constructability
3. The points in the project lifecycle when constructability is addressed
4. The means used to measure success in addressing constructability
5. The relative importance placed on constructability
6. The parties on the project team who should address constructability

Questions were also asked regarding general background information about the respondent and the respondent's firm.

The questionnaires were mailed to design and construction firms located in the states of Washington, Oregon, and Nevada over a period of several years from 1998-2003. The list of design firms was generated from local chapters of the American Society of Civil Engineers (ASCE), the Consulting Engineers Council of Washington (CECW), and the yellow pages in the local phone book. The list of construction firms was generated from the phone book and the member companies of the Association of Building Contractors (ABC) in Washington and the Associated General Contractors (AGC) chapters in Washington and Oregon. No efforts were made to limit the list of firms based on size, type, location, design discipline, trade, or other similar characteristic. The survey distribution and response rate is shown in Table 1.

Table 1. Survey distribution and response rate

State	Designers			Constructors		
	No. of Questionnaires Sent	No. of Resp.	Resp. Rate	No. of Questionnaires Sent	No. of Resp.	Resp. Rate
NV	60	20	33.3%	--	--	--
OR	258	61	23.6%	390	36	9.2%
WA	152	25	16.5%	268	16	6.0%
Total	470	106	22.6%	658	52	7.9%

Designers who responded to the questionnaire worked in firms earning revenues of up to $500 million, with the majority of responses coming from designers in small design firms earning $0-$5 million in annual revenues (76%). A wide variety of facilities are designed by the responding firms with the most prominent being: commercial (67%), office (53%), civil (48%), and single-family residential (42%). While firms may cover more than one design discipline, the primary design service provided by the responding firms was civil (52%), followed by architectural (46%), structural (30%), and transportation (25%). The mean number of years of experience that the designer respondents had in the construction industry (including design) was 26.8 years. In specifically design positions, the mean number of years of experience was 24.9 years which, compared to their overall industry experience, indicates a minimal amount of experience outside of the design field.

Constructors responding to the survey questionnaire included representatives from both general contracting and subcontracting firms (85%) and construction management firms (15%). The responding firms construct a wide variety of facilities, with the most prominent being: commercial (79%), office (56%), industrial (48%), and manufacturing (35%). With regard to the type of work performed collectively by the responding firms, 65% is new construction, 35% renovation, and 11% maintenance. The mean number of years of experience that the respondents had in the construction industry was 25.4 years, with a mean of 23.5 years specifically in construction.

Results

The survey asked whether the respondent's firm formally considers constructability on projects. Ninety-nine of the 106 designers (93%) and 39 of the 52 constructors (75%) responded that they formally consider constructability. This result is encouraging. It shows that addressing constructability has become part of standard practice and that constructability is considered an important lifecycle property. The survey results are perhaps a reflection of the industry's emphasis on minimizing construction cost and reducing project schedules. Additional justification might be found in the fact that a portion of the business of some design firms, especially civil and structural engineering disciplines, is the design of temporary structures on behalf of the constructor. In this case, constructability would also be a prominent concern.

A subsequent question explored the formal consideration of constructability further by asking the respondents to indicate the specific practices employed to address constructability. The responses are summarized in Figure 1. A formal constructability review process (CRP) was cited as the most commonly used practice (71%). This was followed closely by plan reviews (68%), project meetings (62%), and value engineering (VE) reviews (54%) as the practices predominantly used by the designers to address constructability. Use of a company manual to address constructability was only listed by 15% of the designers, which may indicate that a formal constructability resource is not available. The responses from the constructor surveys showed similar results. The practices used by constructors to address constructability were predominantly constructability review processes (63%), project meetings (58%), value engineering reviews (58%), and plan reviews (54%).

For the question related to practices employed to address constructability, it is important to note a distinction between plan reviews, design reviews, and constructability reviews. Plan reviews focus on the quality of the plans, i.e., whether all pertinent information is shown, details are cross-referenced correctly, there are no dimensioning errors, figures are coordinated between disciplines, etc. Design reviews aim to ensure that all design code requirements are satisfied, the design meets the owner's expectations, and standard design practice has been followed. Both of these reviews address aspects of constructability, particularly the objective of clear, concise, and biddable design documents. Constructability reviews address the ease and efficiency with which a project can be built, but as commonly practiced, may include aspects of plan reviews and design reviews as well.

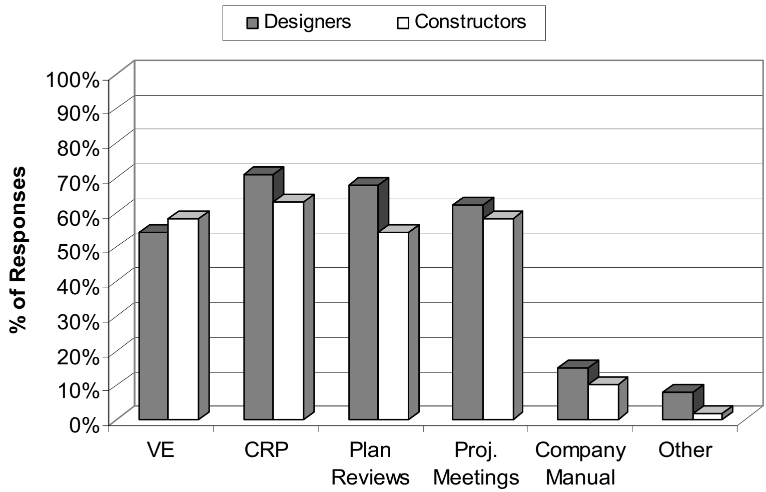

Figure 1. Practices used to address constructability

The large percentage of constructors who participate in constructability review processes is perhaps a reflection of the respondent pool's involvement during the design phase to assist the design team in improving constructability early on in a project or in the pre-construction phase, and possibly of their sometimes functioning as construction managers. Early constructor involvement in a project has been identified as a way to incorporate construction knowledge in the design and improve constructability.

The timing for addressing constructability was also asked. The results for both the designer and constructor respondents are shown in Figure 2. The respondents were allowed to identify any and all phases during which constructability is addressed. Designers indicate that constructability is addressed predominantly in the preliminary engineering and design phases of a project. Seventy-four percent of the respondents from design firms stated that constructability is addressed in these two phases. This was followed by the planning phase (51%) and construction phase (54%). The constructors responded that the construction phase is when constructability is most commonly addressed. Sixty percent of constructors listed construction as the phase when constructability is considered, a result consistent with the typical point in which they enter the project lifecycle. This result is not inconsistent with the constructors' responses regarding the practices employed to address constructability. Since project meetings and value engineering were cited strongly, the respondents may have experience addressing constructability through these mechanisms during the construction and associated pre-construction phases. It is also possible that some of the respondents functioning as subcontractors find opportunities to address constructability when they produce their detailed designs or shop drawings. The construction phase was followed by preliminary engineering (52%), design (52%), and planning (38%) as the most common phases in which constructability is addressed.

Figure 2. Project phases during which constructability is addressed

With regard to the members of the project team who should address constructability, the results point heavily toward the designer and constructor (see Figure 3). The respondents could select owner, designer, constructor, construction manager, all, or none. The designers suggested that constructors and designers as the primary parties to address constructability, with approximately the same frequency (78% for constructors and 75% for designers). However, the constructors cited themselves as the primary party (56%) and the designers to a lesser extent (46%). Although the difference has not been statistically validated, the results indicate that designers consider themselves as playing more of a significant role in addressing constructability than do the constructors. This is consistent with the significant impact that can be made on constructability early on in a project lifecycle. The high percentage given to constructors as parties who should address constructability coincides with the significant impact which they can provide on constructability given their construction knowledge, and the results of the previous question regarding the project phase in which constructability is addressed. Approximately 30% of both the designer and constructor respondents indicated that all parties should address constructability, perhaps reflecting a perspective that all parties can have some input and impact. Another view of these results is that designers see themselves in partnership with constructors and playing a preeminent role in addressing constructability. Constructors perhaps share a similar opinion but additionally see a more balanced distribution of responsibility between owner, designer, and constructor, with themselves providing the strongest input.

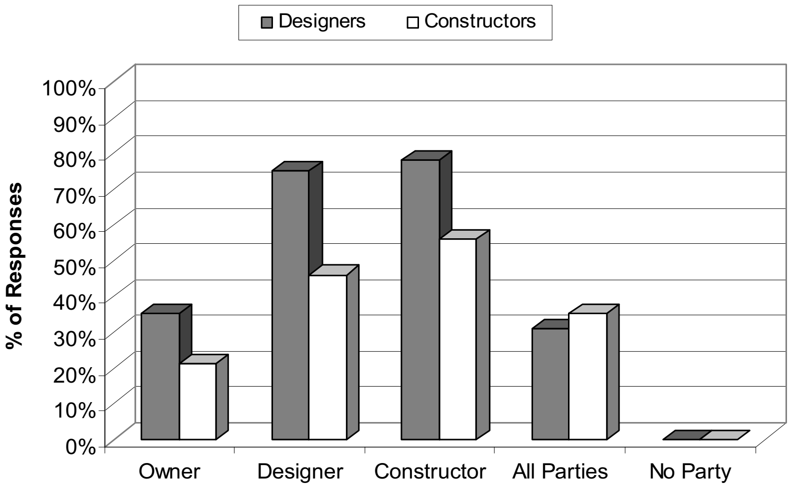

Figure 3. Opinions regarding which project team member(s) should address constructability

The respondents were asked to rank the lifecycle properties in the order of importance to success in achieving maximum value in the constructed facility. The properties to be considered in the question were: designability, constructability, maintainability, operability, recommissionability (reconstructability), and decommissionability (deconstructability). Definitions for each of these terms were provided with the survey and may be found in the report by Gambatese and Dunston (2003). The responses to this question are shown in Figure 4 with a higher number indicating greater importance to success in achieving maximum value from the project (1 = lowest ranking, 6 = highest ranking). Based on the responses, designers place the greatest importance on operability (4.96) followed, in decreasing order of importance, by constructability (4.75), maintainability (4.39), and designability (3.51). Constructors, however, place the greatest importance on constructability

(5.16). This is followed by operability (4.89) and maintainability (4.44). In reflection of the commonly held short-term view of the project lifecycle, recommissionability (2.41) and decommissionability (1.17) are not given much importance. The importance which constructors place on constructability is expected given its potential impact on their scope of work. Altogether, the results illustrate a shared opinion that the most important lifecycle properties correspond to those phases that are typically deemed to incur the greatest cost to the owner, i.e., construction and operations/maintenance.

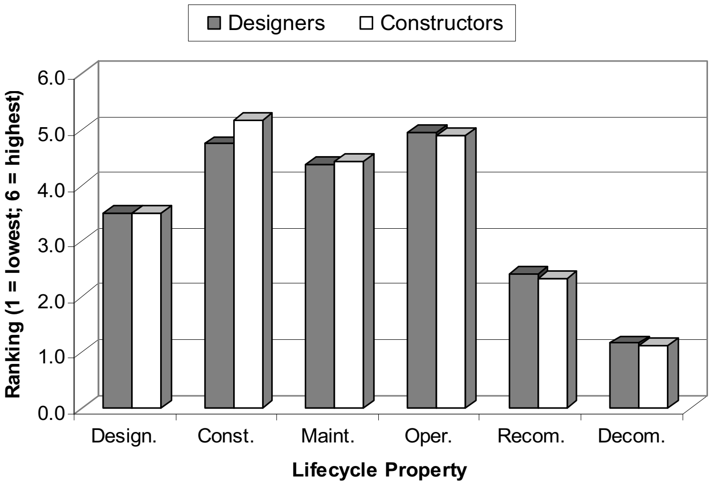

Figure 4. Relative importance of constructability versus other lifecycle properties to achieving project success

Another survey question asked about how success at addressing constructability was measured. Indicators of enhanced constructability might be a minimal number of change orders and requests for information (RFI's), reduced construction cost or cost escalation, shorter schedules or schedule slippage, and a higher quality product. The results from this question are provided in Table 2. Designers primarily use constructor feedback, construction cost, the number of change orders, and the number of RFI's to measure performance in the area of constructability. Final construction cost (a reference to cost escalation), the number of RFI's and change orders, adherence to project schedule, and owner feedback are metrics most commonly used by constructors.

Table 2. How success at addressing constructability is measured

Respondent	Metric	% of Responses
Designers (n = 106)	Constructor Feedback	64%
	Construction Cost	59%
	# of Change Orders	55%
	# of Requests for Information	54%
	Owner/Peer Feedback	29%
	Construction Support Billings	28%
	Construction Support Staffing	28%
	Design Services Staffing	10%
	Design Services Billings	4%
	No Measures Used	8%
Constructors (n = 52)	Final Construction Cost	40%
	# of Requests for Information	35%
	# of Change Orders	33%
	Adherence to Project Schedule	27%
	Owner Feedback	25%
	Pre-construction Job Costs	19%
	Construction Staffing	17%
	Pre-construction Staffing	15%
	No Measures Used	4%

Given that this investigation has surveyed practitioners in only three states in the western region of the United States, and that the response rates were low, caution is advised in extrapolating the results to the broader U.S. construction industry. It is possible that the respondents were somewhat self-selective because their organizations already regard the topic and implementation of constructability as priorities in their day-to-day practice. On the other hand, the fact that the surveyed states are not among those containing high numbers of large construction markets as states like California, New York, or Texas, might be an indication that this message has penetrated beyond such large markets to practice in the smaller construction markets. A more extensive survey is needed to clarify this question.

Conclusions and Recommendations

The viability of enhanced constructability is predicated on the involvement and interest of project team members. Designers and constructors, the parties predominantly involved in addressing and improving constructability, must have a motivation to act. The barriers to considering constructability must not be so great as to inhibit designers and constructors. In addition, the benefits of enhanced constructability must be at such a level that they motivate designers and constructors. The removal of barriers and the presence of motivating factors make considering constructability viable.

Improving constructability is a viable undertaking in the construction industry and a current part of standard practice. This research study revealed that both designers and constructors participate in the process and employ a variety of different practices to address constructability. Designers see themselves and constructors as primary participants in the process to improve constructability. Clearly both are important, with the designer providing the requisite design knowledge and the constructor contributing knowledge of construction means and methods. The importance of constructability to the success of a project is recognized by both designers and constructors. Both parties rank constructability highly along with operability and maintainability.

Current practice includes formal consideration of constructability. This is important in light of the growing emphasis on sustainability and the period of infrastructure renewal that the country now faces. In order to maintain the extent and improve the success of practice regarding this lifecycle property, there should be a clear understanding of the shared responsibilities between project parties. Part of attaining this understanding is a realization by designers that their role is embodied within the construction industry and not adjunct to it, and that constructors can play a role in, and provide value to, the design process. The further objective of this investigative study is to ascertain the impressions and practices of the remaining major project team members and pursue an agenda for formalizing the properties that are now given considerably less formal attention.

Acknowledgment

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Constructability Issues and Review Processes

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Abstract

The objective of any constructability review process is to identify elements of a project that can be modified to make the project easier to bid and to build. Such a review can help minimize the number and magnitude of change orders, disputes, cost overruns, and delays during construction. This involves enhancing the input of construction knowledge and experience during the design and planning stages of a project. The type of construction, scale of a project, and owner will influence the implementation of a constructability review process. This paper reports the results of a study that examined how to implement a constructability review process on projects for a state transportation agency. This paper summarizes different approaches for constructability reviews, the barriers to their success, as well as the review process that is currently being adopted by the Kentucky Transportation Cabinet.

Introduction

At its finest, constructability is the integration of design and construction knowledge during the early stages of a project development process to insure the project is buildable, cost effective, biddable, and maintainable. Although designers have always addressed the engineering and aesthetic requirements of a project, the practice of addressing how well their designs can be built and maintained is still a relatively new process. Until the integration of design and construction knowledge is fully achieved among the participants of the project development process, the practice of constructability reviews is necessary.

Constructability is a concept that has existed since the 1980s in the construction industry (CII 1986). Prior research has shown that enhanced constructability benefits not only the construction aspect of a project, but the operating and maintenance phases as well (see Table 1).

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Table 1. Benefits of enhanced constructability

Project Phase	Benefit
Construction Only	"Buildable" plans and specification (AASHTO 2000)
	Biddable plans and specifications (AASHTO 2000)
	Reduced construction cost (CII 1993)
	Shortened construction schedules (CII 1993)
Construction, Operation and Maintenance Phases	Improved project quality (CII 1993)
	Improved safety (CII 1993)
	Improved risk management (CII 1993)
Operation and Maintenance Phases Only	Improved maintainability (CII 1993)
	Improved operability (CII 1993)
	Improved reliability (CII 1993)

With so many potential benefits to be gained from improving constructability, it is not surprising that many engineering, construction, and owner agencies are working to implement at least some aspect of constructability reviews into their project development process.

This paper summarizes the factors that need to be considered when implementing a constructability review process, the barriers to their success, and an overview of the review process that is currently being adopted by the Kentucky Transportation Cabinet.

Aspects of a Constructability Review Program

A constructability review process already exists for many public and private agencies in the engineering and construction industry. Although one process does not apply to every agency, previous research has identified common elements that have proven to be most successful:

1. *Champion*: A constructability program needs a champion to oversee its implementation. It is recommended that the champion be from senior management and that part of their job be to emphasize the team concept ensuring cooperation and that communication flows freely, both vertically and horizontally. The champion should also have the authority to approve plans and specification revisions when a constructability review uncovers a significant problem.
2. *Teams and their composition*: Due to their multidisciplinary nature, it is not effective for just one person to perform a constructability review of a project. Instead, teams of individuals from different agencies and backgrounds are needed to not only identify project issues impacting productivity but to also propose solutions as well. It is important to keep the team as small as possible and at the same time provide the required expertise for the project to be reviewed. The team should be composed of:

- Construction professionals (active or retired);
- Internal construction staff;
- Consultants (i.e. designers), who may be retained on either a project-by-project basis or used on an "on-call" basis for multiple assignments while keeping in mind that it is recommended for the consultants not to review their own designs;
- Regulatory representatives;
- Utilities representatives;
- Railroad representatives;
- Material suppliers (on projects where non-standard materials are to be used); and
- Maintenance representatives.

3. *Frequency of reviews*: Most agencies that incorporate a constructability review process perform multiple reviews; each performed at different stages of project development. The frequency of reviews is determined by considering the agency's resources and scope of the project. For example, the California Department of Transportation (Caltrans) has identified three levels of reviews based on project type (AASHTO 2000):

    - *Level 1 constructability review*, which includes reviews at the project initiation document (PID) stage and the 30%, 60%, and 95% design stages. This level of review is applied to roadway projects involving new roadway construction and improvement of existing roadways either of which involves complex traffic phasing, complex interchange construction, and significant utility involvement.
    - *Level 2 constructability review*, which includes reviews at the PID stage and the 30% and 95% design stages. Occurring less frequently than Level 1 reviews, these reviews are applied to projects with less complex roadway projects and less complex structures. Most of Caltrans rehabilitation projects fall under this category of review.
    - *Level 3 constructability review*, which includes a PID stage review and a 95% design review. This level of review is applied to simple scenarios such as maintenance projects.

    In general, reviews conducted during the early stages of design have the best potential for providing meaningful benefits with minimum delay and cost. However, advantages exist with reviews conducted early in the project development process versus those conducted later in the process. Early reviews may be conducted on plans that still lack many details and have not been developed to the point before all constructability issues can be addressed. Later reviews on plans that have been developed to a further level of completion can sometimes be more difficult to change. In some cases, owners and designers may be committed to certain design aspects and reluctant to change designs due to either the level of resources of time and money already expended on the plan or to commitments that may have been made to outside agencies and project stakeholders in order to secure approval of their plans.

4. *Resources*: In developing a constructability review process, agencies should avoid creating a process that is complex and resource intensive. The ideal process should be simple to implement and should focus on the major issues involved in the project. Agencies need to adjust the constructability process to fit their goals, realizing that the following variables will affect the program:

    - *Manpower*: More resources may be required in the early phases than the later phases;
    - *Funding*: Savings from reduced change orders and claims will typically offset possible additional funding for the reviews earlier in the project schedule; and
    - *Time*: the process may impact some project schedules but any time lost in the design phase will typically be recovered in the construction phase due to a more constructible and maintainable project.

5. *The review process*:

    - *Type and length of review meeting*: Ideally, the agenda of the reviewers must be organized to complete the constructability review in one meeting and should include specific items of concern to the design as well as the construction contractor, while allowing time for discussion and to resolve any issues. The review should also allow reflection on previous decisions and determine whether the project is on track with respect to scope, schedule and cost.
    - *Checklist*: Many agencies have found it imperative that certain guidelines and checklists be developed for the review. Some agencies have found that general checklists are appropriate while other agencies have developed detailed checklists of items based on lessons learned that have historically caused constructability problems.
    - *Responsibility for review follow through*: It is also recommended that the constructability review plan include a mechanism that follows through on the comments produced during the review (AASHTO 2000). Most agencies have the project manager review the comments provided and reply back to the reviewers with what was or was not included in the design. It is also recommended that the plan have a resolution procedure that assigns responsibility for deciding whether review comments will be incorporated into the project design.

- *Dissemination of review comments*: While review comments will obviously be useful to the specific project being reviewed, it is also important to disseminate and archive the lessons learned for future projects. Different agencies accomplish this task by developing a lessons learned system. The transportation agencies in Washington and Maine store their lessons learned for future reference by designers/agency staff. Maine also posts their results on their Internet home page.

6. *Measuring constructability review results and benefits*: It is difficult for agencies to effectively measure the cost and benefits of constructability reviews other than through anecdotal results. Research by Dunston et al. (2002) included a case study of two roadway projects in Washington State that underwent a constructability reviews, which estimated that the benefit to cost ratio for performing the reviews were 2.10 and 2.29. Regardless, quantifying the costs and benefits will improve the efficiency of current reviews and also ensure the viability of future reviews by quantifying the return on investment of conducting reviews.
7. *Post construction reviews*: Post construction reviews allow agencies to eliminate repeated mistakes that increase costs and affect project scheduling, as well as provide design with feedback on issues that can be addressed in the future. It is important for post-construction reviews to:

    - Have a champion to lead the process;
    - Provide benefit to the owner agency; and
    - Include external representatives who are familiar with the project and the issues that occurred during construction.

Although the term, "Post Construction Reviews" implies that these occur after construction is complete, it is best to perform these reviews prior to this point. If conducted at say 90% of construction completion, most of the parties involved in construction, including specialty contractors, will still be involved in the project and have their personnel on site. This makes the reviews easier to perform and also ensures that lessons learned from construction are still fresh in the participants' memory. Agencies conducting post-construction reviews should also have a mechanism for distributing and sharing the review with all parties involved in the project.

A Constructability Review Process for the Kentucky Transportation Cabinet

The authors developed a constructability review process for the Kentucky Transportation Cabinet (herein referred to as Cabinet), that was specifically designed to support the Cabinet's project development process.

Research Surveys

In order to better understand how a constructability review process could be implemented within the Cabinet, the researchers conducted two separate surveys. The first survey involved 19 state transportation agencies that were identified by prior research (Anderson and Fisher 1997) as having existing constructability review programs. The state transportation agencies were asked what they consider to be the biggest barriers to constructability review efforts within their agencies. The barriers were categorized into four categories as shown in Table 2.

Table 2. Barriers to constructability

Barrier	Frequency
Lack of time	12
Lack of available manpower	7
Lack of available experience	6
Contractor reluctance	3

Note: Surveyed states included: AK, CA, CT, FL, IN, KS, KY, MO, MD, MI, NJ, NV, NC, OR, OH, SC, SD, TX, and VA.

Lack of Time. Due to project development deadlines, twelve (63%) state transportation agencies indicated that an insufficient amount of time exists for constructability review programs. Prior research has also found the availability of time to be a limiting factor to constructability reviews (CII 1993; AASHTO 2000). One state transportation agency indicated that it was very difficult to find a stage during the project development process when plans were complete enough for contractors to review and make suggestions and yet also be at a stage when designers felt they could incorporate the changes without experiencing major setbacks in meeting their project deadlines.

Lack of Available Manpower. Seven (37 %) state transportation agencies indicated that there is not enough personnel to staff their constructability review programs. Although previous research also identified available manpower as a barrier to constructability, its frequency ranked higher with our study. A study by the Construction Industry Institute (CII 1993) ranked available manpower as the 18th most common barrier out of a total of 18 identified barriers. Furthermore, a study by the American Association of State Highway and Transportation Officials (AASHTO 2000) ranked available manpower as the 8th most common barrier out of a total of 16 issues. One possible reason for the increased frequency is a shortage of personnel in numerous state transportation agencies. Another possible reason for the increase is that constructability review programs are attempting to become more intensive thereby requiring more manpower.

Lack of Available Experience. On a similar note, a lack of experience for conducting constructability review programs was indicated as a significant barrier by 6 (32 %) state transportation agencies. They indicated that many designers lacked construction experience and, similarly, many contractors lacked design experience or an understanding of design criteria. Previous research suggests that a lack of construction experience on behalf of designers is indicative of two occurrences: (1) a perception that construction knowledge is not considered valuable among design personnel, and (2) few opportunities exist for site visits by designers (CII 1993; AASHTO 2000).

One tool that can be helpful for a constructability review program is a lessons learned database that captures and archives construction knowledge to be used in future project developments. Lessons learned databases have been developed for different state transportation agencies with varying degrees of success in their implementation. The study's survey asked each state transportation agency if they had a formal lessons learned system. Unfortunately, only one state transportation agency (Texas) replied that they did. Previous research indicates that system sustainability and quality of the stored lessons are critical to the success of lessons learned systems.

Contractor Reluctance. Three (16%) state transportation agencies indicated that reluctance on the part of contractors to participate in a constructability review program exists. Some contractors fear they will loose their competitiveness by divulging proprietary construction means and methods to competing construction firms through their participation. One approach to alleviate this problem is the use of retired construction professionals, who can typically be identified through local highway construction associations.

In order to understand how other state transportation agencies conduct their construction review program, the research also asked state transportation agencies with a constructability review program to indicate when they conduct their constructability reviews. The results are shown in Table 3. (Note: Percentages of design completion are based on the percentage of the scope of work completed.)

Table 3. Stages of construction input to design

Project Development Phase	Frequency
Planning	3
30% Design Completion	12
60% Design Completion	10
90% Design Completion	9
Post Bid	7

It is important to note that the categories in Table 3 are not mutually exclusive. Although the design stages shown in Table 3 are not universal design milestones among different state transportation agencies, there is still clear evidence that constructability reviews commonly occur more than once in the project development process.

Next, the research examined the resources used for the constructability reviews by asking state transportation agencies who was used to help conduct the reviews. As shown in Table 4, state transportation agencies used both in-house and outside parties in their review process.

Table 4. Sources used to conduct constructability reviews

Sources for Construction Input	**Frequency**
In-house Personnel	17
Outside Construction Firms	9
Consultants and other outside sources (for example, retired contractors)	9

All but two of the surveyed state transportation agencies (11 %) indicated that they use in-house personnel. Outside personnel included construction firms, consultants, and other parties, such as retired individuals of the state transportation agency and retired individuals of construction firms.

Although occurring either towards the end of construction or after project completion, the research also examined the use of post construction reviews, since these reviews can be an effective means of reporting the outcomes of the construction process back into their design process, especially for the purpose of documenting the lessons learned during construction. Of all the state transportation agencies that responded, 53% (10 states) currently have a formal post construction review process. Finally, 33% (6 states) of the surveyed state transportation agencies with a formal post construction review process involve the same participants in both their constructability reviews and their post construction reviews.

Constructability Issues Occurring on Cabinet Projects

Before beginning design of a constructability process for the Cabinet, the study surveyed 20 project resident engineers within the Cabinet (resident engineers serve as the on-site Cabinet representative during construction) and 22 project engineers and project managers with highway contractors to identify frequently occurring problems in the construction process. Furthermore, each respondent was asked to assess the impact of each constructability issue in terms of cost, schedule, and quality on a project on a scale of 1 to 5 (1 indicating no impact and 5 indicating tremendous impact). This allowed the study to develop a constructability review process that could effectively address these issues. The study identified 62 different constructability issues and categorized them by type; the top 5 categories identified by both the Cabinet and contractor personnel are shown in Table 5. Although some of the issues may be unique to Kentucky, many of the issues exist on highway projects throughout the United States.

Table 5. Highway constructability issues and impacts (combined owner and contractor perspective)

Constructability Issue Category	Number of Different Issues	Average Cost Impact (Scale 1-5)	Average Schedule Impact (Scale 1-5)	Average Quality Impact (Scale 1-5)	Average Overall Impact
Utilities	17	3.6	4.8	2.9	3.8
Traffic Control	11	3.9	3.7	3.4	3.7
Geotechnical	10	3.8	4.0	2.7	3.3
Right-of-Way	9	3.7	3.9	2.3	3.3
Structure	7	4.3	3.4	2.3	3.3

The top five categories of constructability issues identified separately by cabinet and contractor respondents are shown in Tables 6 and 7. Although there are some differences in perspective of the most recurring constructability issues, it is clear that both groups have similar concerns, particularly in the area of utilities, traffic control, and right-of-way.

Table 6. Constructability issues and impacts (owner perspective)

Constructability Issue Category	Number of Different Issues	Average Cost Impact (Scale 1-5)	Average Schedule Impact (Scale 1-5)	Average Quality Impact (Scale 1-5)	Average Overall Impact
Utilities	4	4.1	4.8	3.2	4.0
Water Drainage	3	4.3	3.4	3.2	3.6
ROW	2	4.2	4.1	2.3	3.5
Inadequate Plans	4	3.4	4.3	2.2	3.3
Traffic Control	4	3.8	3.2	2.4	3.1

Table 7. Constructability issues and impacts (contractor perspective)

Constructability Issue Category	Number of Different Issues	Average Cost Impact (Scale 1-5)	Average Schedule Impact (Scale 1-5)	Average Quality Impact (Scale 1-5)	Average Overall Impact
Traffic Control	7	3.9	4.0	4.0	4.0
Utilities	13	3.7	4.6	2.8	3.7
Geotechnical	9	3.7	3.6	2.6	3.3
ROW	7	3.6	3.9	2.3	3.3
Structure	7	3.0	3.4	2.3	3.3

Overall, the most recurring constructability issue involved new and existing utilities. Respondents indicated that utilities have the greatest impact on the project's schedule. Specific problems with utilities include:

- Trouble locating existing utilities before construction begins;
- Construction delays due to utility relocation;
- Unforeseen existing utilities that interfere with proposed construction;
- Utilities relocated incorrectly; and
- Existing utilities in locations other than shown on plans.

Many of the suggested resolutions to the utilities' issues involved improving the communication between utility agencies, the Cabinet, the designer, and the contractor by including the utility agency very early in the project development process. It was noted by many respondents that utility companies sometimes delay relocating existing utilities due to past experiences of witnessing highway projects delayed a number of years before construction actually begins. By including utility companies in the project development process, utility companies should have a better understanding of the overall project schedule (including planning, design, and construction) and would be better able to plan and execute utility relocation without interfering with the project milestones. Other respondents suggested that existing utilities should be differentiated as either critical or non-critical in terms of their impact on the project schedule. Finally, the Cabinet should establish a policy that all critical utilities are to be successfully relocated before construction begins.

Traffic control was found to be the second most common constructability issue, and its greatest impact is on project cost (Table 5). One reason why traffic control is a common constructability issue on highway construction projects is that most current highway projects involve rebuilding and/or expanding existing roadway systems. Furthermore, state transportation agencies are making commitments to the public to minimize disruption to traffic flows and reduce congestion due to construction activity. As a result, contractors are faced with the task of diverting and controlling large volumes of traffic while simultaneously building a project. Traffic control is particularly problematic on bridge decks where clearance between traffic lanes and construction is often limited due to the bridges' physical dimensions.

Respondents offered a number of suggestions about how traffic control could be improved on future projects. Many respondents suggested that highway shoulders should be designed to support temporary road lanes to allow rerouting of traffic on future projects. Respondents also expressed the opinion that the only effective method to control traffic speeds through the work zone is the presence of law enforcement personnel; therefore, respondents strongly urged their presence, if at all possible, on future projects. The presence of law enforcement personnel in the work zone may not always be possible due to budget restraints and work regulations for police (some law enforcement personnel are restricted from working second jobs). Therefore, it was suggested that criteria be developed to identify which projects should have priority for this type of assistance. It was also suggested that, if possible, bridges in rural areas should be closed during construction to allow more expedient completion of the project. Traffic could either be rerouted or a temporary bridge could be used. This type of decision would obviously need to be made very early in the project development process (at the 0% to 30% design stage). Finally, many respondents reported it was key to communicate with the public regarding plans and progress of both current and future construction roadway activity. Although it was not noted by the survey respondents, scheduling roadway construction activities during off-peak hours, such as at night, will also minimize the impact on traffic flows through a work zone.

Geotechnical issues were the third most common constructability concern, and its greatest impact is on project schedule (Table 5). This may be reflective of the unique karst geology that exists throughout much of Kentucky. The most common geotechnical issues involved unforeseen rock or soil conditions that require construction change orders. It was suggested that the placement of bore holes for geotechnical investigations be considered in constructability reviews during the early stages of the project development process.

Issues involving *right-of-way* was another significant constructability concern of both the Cabinet and contractor personnel, and its greatest impact is on project schedule (Table 5). Many respondents expressed the concern that due to urbanization, the Cabinet will be required to negotiate with increasingly more landowners on future highway construction projects. As a result, right-of-way issues will become even more prevalent. Some of the problems involved:

- Right-of-way agreements not secured prior to construction, thus causing delays;
- Differences between what is shown on plans and what was agreed to between land owners and the Cabinet in right-of-way agreements;
- Plans having not enough detail during right-of-way negotiations;
- Not enough space in right-of-ways for construction activities; and
- Schedule of securing right-of-way agreements not coinciding with the project's construction schedule.

There was a wide array of resolutions offered to help solve right-of-way issues. Many respondents felt that projects should not be released for construction until right-of-way agreements have been secured for, at least, the initial stages of construction. It was suggested that three-dimensional graphical models could be used to better display to landowners what will occur on their property during construction (for example, what a 4:1 slope will actually look like). Besides right-of-way agreements giving more attention to the amount of space available to the contractor, it was suggested that temporary easements be used to secure additional room, thereby avoiding costs of additional land purchase on behalf of the Cabinet.

Constructability Review Process Design

A constructability review process obviously needs to address commonly occurring problems during the construction process. Meanwhile, the process needs to adhere to the time and cost restraints. An effective constructability review process for a transportation agency must follow an established methodology similar to value engineering. The process must be flexible enough to apply to all types of projects handled by the agency. Furthermore, the process must address the critical issues impacting transportation construction projects, such as ease of construction, environmental factors, construction phasing and scheduling, project safety, and accommodation of future maintenance and operations. To obtain maximum benefit from a constructability review, it must be initiated early in the planning phase of the project and continue through design and construction. There are several tools that can be used to implement this process, such as the capture and utilization of "lessons learned" on previous construction projects.

When developing a constructability review process for the Cabinet, a major factor that was considered was the Cabinet's project development processes as shown in Figure 1. As plans progress through the development process, different issues need to be addressed as design issues are addressed. The review process was designed to address these issues as they are identified by different parties throughout the process. The proposed formal process consists of suggested sample checklists and a suggestion form that are designed to provide a guide for the phase reviews. The checklists were based heavily upon the work of the AASHTO Subcommittee on Construction and input from other STAs. The suggested checklists were developed as tools, and indicate the minimum documentation required for a complete project submission. Comments should not be limited to items on the checklists. Opportunities for constructability input during the project decision-making process for Cabinet projects are discussed in detail in the following sections.

Planning Phase

The planning phase (Table 8) is the first component of the Phase I design milestone. In this phase, the Cabinet determines the project purpose and needs. An initial assessment of environmental overview, project timing requirements, and special problems and limitations such as ROW and utilities are discussed. During the planning phase, the Cabinet conducts a public meeting(s) in order to understand community issues and concerns and engage the public in the early stages of project problem solving.

The Cabinet's constructability review process comprises in-house construction experts involved in public meeting(s) to attend in 'observation mode' so that they can see first hand issues raised by the public. The research also suggests that depending on the size and need of the project, detailed studies of the issues may be performed by the Cabinet's construction division.

Table 8. Planning phase agenda and opportunities for constructability input

"Phases of Current Project Development Process"	**Opportunities for Constructability Input**
Planning Phase [Phase I Design]	
• Determine project purpose and needs. • Conduct Environmental overview. • Establish project timing requirements • Identify project special problems and limitations. • Conduct public meeting.	• Get construction experts involved in public meeting to attend in 'observation mode.' • Some projects must perform a detailed study of the issues by including input from construction division.

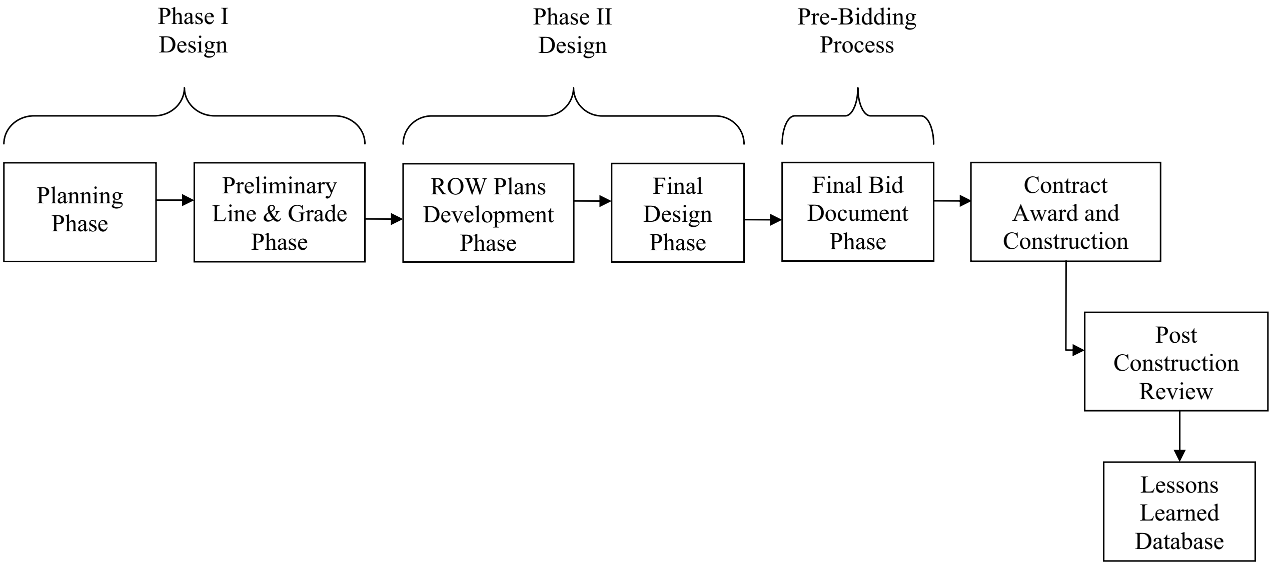

Figure 1. Kentucky Transportation Cabinet project development process

Preliminary Line and Grade (PL&G) Phase

The Preliminary Line and Grade phase (see Table 9) is the second component of the Phase I design milestone. In this phase, assessments of a project's environmental impact are developed through the environmental document and critical issues involving right-of-ways (ROW), utilities, and railroads are identified and discussed in detail. During this phase, alignment and grade are selected, public meetings are conducted, and the project team verifies that project goals and objectives are being met. Also, compatibility studies on future projects are performed where feasible.

The researchers suggest using in-house constructability consultants that have expertise in fields such as ROW, utilities, railroad, environmental, among others based on specific project requirements. The researchers also suggest a geotechnical review of the proposed plan, line, and grade (PL&G) either through a consultant or retired geotechnical expert. Depending on the size and need of the project, soliciting input from an outside contractor is another option to consider. The outside contractors can be identified from industry associations. In this case, the Cabinet refers its requests to the Kentucky Highway Contractor Association (KHCA). Table 9 shows some of the suggested checklists to use during the PL&G phase.

Table 9. PL&G phase agenda and opportunities for constructability input

"Phases of Current Project Development Process"	**Opportunities for Constructability Input**
Preliminary Line and Grade (PL&G) Phase [Phase I Design]	

• Determine if project objectives (purpose & needs) being met.
• Environmental Document developed
• Identify critical ROW issues.
• Identify special problems with utilities, railroads, etc.
• Public involvement required.
• Select corridor (line and grade).
• Compatibility study for future projects where feasible.
	• Bring on In-house constructability consultant.
	• Solicit input from outside contractor (retired construction contractors) that is dependent on project size and need.
	• Use KHCA as a source to obtain construction personnel.
	• Geotech review of PL&G (either consultant or retired geotech).
	• Suggested checklist to use:
	    • Preliminary Design checklist
	    • Clearing/Grubbing/Excavation checklist
	    • Removal/Demolition checklist
	    • Environmental checklist

As an example, the Environmental checklist is shown in Table 10. The checklists developed as part of this research effort represent a culmination of issues that are typically reviewed by other STAs. They were intended to help the Cabinet begin the constructability review process. It is intended that as the constructability review process continues, recurring issues that may be unique to the Cabinet will be identified in the Cabinet's Lessons Learned System which would then be used to modify the checklists in the future.

Table 10. Environmental checklist

KENTUCKY TRANSPORTATION CABINET

CONSTRUCTIBILITY REVIEW CHECKLIST

ENVIRONMENTAL CHECKLIST

PROJECT TITLE: ____________________

PROJECT ID NO.: ____________________ DESIGN PHASE: ☐ 30 ☐ 60 ☐ 90

NAME OF REVIEWER: ____________________ DATE: ___/___/____

Item No.	Item to be Checked	Yes	No	N/A
1 EC	Are erosion and pollution control items/measures shown?			
2 EC	Is depiction of all existing trees and shrubs to remain and those to be removed shown on plans?			
3 EC	Have all permit requirements been addressed?			
4 EC	Are local agency requirements clearly identified in either plans or specifications?			
5 EC	Are provisions to prevent groundwater contamination and other environmental pollution addressed in either plans or specifications?			
6 EC	Are provisions for noise abatement (e.g., permanent noise wall, alternative construction schedule) considered?			
7 EC	Are landscaping and planing requirements and their conflicts with utilities (e.g., irrigation lines) verified?			
8 EC	Is there sufficient space for power mowers around proposed tree plantings?			
9 EC	Is compliance with all applicable or relevant and appropriate environmental and public health requirements identified?			
10 EC	Are all substantive permit requirements clearly identified in the design with a description of the means of demonstrating compliance?			
11 EC	Have all required off-site permits been applied for by the designer?			
12 EC	Are all performance standards clearly identified?			
13 EC	Has perimeter air monitoring been specified?			
14 EC	Are dust and noise control measures specified?			
15 EC	Were provisions in plans and/or bid documents for silt fences, turbidity barriers, etc considered?			

Suggested Changes: (to be completed for items checked "NOT OK")

Item No.	Explanation of Change/Addition
Designer's Comment	

Completed By: ____________________ **Sign:** ____________________ **Date:** ____________

ROW Plans Development Phase

The ROW Plans Development phase (see Table 11) involves a critical review of project purpose and need, preliminary quantities, bridge requirements, and construction erosion control plans. Furthermore, signalization, maintenance of traffic, phasing, ROW and utilities plans, plus railroad needs are identified and developed. It is during this phase that ROW, drainage, structure, and geotech plans are finalized.

Table 11. ROW plans development phase agenda and opportunities for constructability input

"Phases of Current Project Development Process"	**Opportunities for Constructability Input**
ROW Plans Development Phase [Phase II Design]	

• Critical review of project objectives (purpose & needs).
• Review preliminary quantities of project objectives.
• Identify Signalization, Maintenance of Traffic, phasing needs.
• Construction Erosion Control plans.
• Develop ROW and Utilities Plan plus RR.
• Final ROW.
• Finalize drainage, structure, geotech design.
• Critical review of bridge requirements (understand the project design context).
	• Early In-house input; if needed bring in external consultant for VE study.
	• Solicit utility coordination input (KU).
	• Constructability input requested from construction, traffic & maintenance, geotech branch, bridge design, utilities, and ROW experts.
	• Suggested checklist to use:
	  • Structures checklist
	  • Utilities checklist
	  • Drainage checklist
	  • Maintenance of Traffic checklist
	  • Schedule/Phasing/Access checklist
	  • Site survey/plan/profile checklist

The research team suggests early in-house input during the critical review and identification process of various issues as noted above. Each highway district in Kentucky has a full-time utility coordinator whose purpose is to interface with utility agencies impacted by the Cabinet's construction and maintenance activities. Soliciting input from the utility coordinator is critical when ROW, utility, and rail road plans are developed. With designs involving sufficient detail at this point and without commitments being made prohibiting significant changes, it is also suggested that any required or desired Value Engineering reviews (usually by external consultant) be done during this phase. Table 11 shows some of the suggested checklists to use during the ROW Plans Development phase and identifies the internal input needed.

Final Design Phase

The Final Design Phase (see Table 12) is the second component of the Phase II design milestone. In this phase, maintenance of traffic, signalization, signs and striping plans are finalized. Special notes, traffic and community impact studies, project objectives and criteria, and bridge design requirements are also reviewed.

Once again, the researchers identified construction parties to provide input into design and to participate in the reviews. The research team suggests seeking input from both the resident and construction engineers. Resident engineers serve as the Cabinet's on-site representatives during construction. Resident engineers with the Cabinet are supervised by their respective construction engineer assigned to each district. During this phase, constructability input is requested from construction, traffic and maintenance, utilities, and ROW experts. Table 12 shows some of the suggested checklists to use during the Final Design Phase.

Table 12. Final design phase agenda and opportunities for constructability input

"Phases of Current Project Development Process"	**Opportunities for Constructability Input**
Final Design Phase [Phase II Design]	

• Review project objectives (purpose and needs) and criteria.
• Review Bridge Design(s) and requirements.
• Finalize final Maintenance of Traffic plans, signalization, signs and striping plans.
• Review Special Notes requirements (blasting, environmental, historical, etc.).
• Finalize construction restrictions (timing, work restrictions, etc.).
• Review traffic and community impact studies.
	• Get resident and construction engineer input.
	• Constructability input requested from construction, traffic & maintenance, utilities, and ROW experts.
	• Suggested checklist to use:
	  • Drawing/Title page checklist
	  • Claims prevention checklist

Final Bid Document Phase

The Final Bid Document phase (see Table 13) involves obtaining right of entry on all ROW parcels, reviewing all bid items to see if they are current, checking and updating utility impact notes, having necessary permits obtained (environmental, water, historical), and reviewing the documents for biddibility.

The research team suggests using in-house personnel to conduct the final bid document phase in order to ensure the biddibility of the documents before the contractors bid on the project. Table 13 shows the suggested checklist to use during the Final Bid Document phase.

Table 13. Final bid document phase agenda and opportunities for constructability input

"Phases of Current Project Development Process"	**Opportunities for Constructability Input**
Final Bid Document Phase	
• Review of documents for biddibility (timing restrictions, specifications, materials, etc.). • Obtain right of entry on all ROW parcels. • Review all bid items to see if they are current. • Review and update necessary permits obtained (environmental, water, historical, etc.). • Check to be sure utilities are relocated or utility impact notes are reviewed and updated.	• In-house personnel conducts final bid document phase. • Suggested checklist to use: • Pre-bid checklist

Post Construction Review

In the past, the Cabinet conducted post construction reviews after the end of construction. Unfortunately, many of the project participants, particularly contractors, were unable to participate due to their involvement on other projects. As a result, post construction reviews (see Table 14) are now performed before or at 90% of project completion. The purpose of a post construction review process as part of the constructability review process is that it provides feedback to representatives from the highway department, the contractor, and the designer organizations regarding the recently finished project. Furthermore, the advantages of post construction review processes are:

- Helps eliminate repeated mistakes in future projects;
- Helps in the modification of specifications in order to eliminate repeated mistakes in future projects;
- Increases communication between different parties; and
- Addresses maintenance concerns on the recently finished project.

The review's meeting minutes are sent to the Cabinet's Central Office in Frankfort and the Cabinet's Value Engineering Section reviews the minutes to recommend new items for the Lessons Learned System (Figure 2).

Table 14. Post construction review agenda and opportunities for constructability input

"Phases of Current Project Development Process"	**Opportunities for Constructability Input**
Post Construction Review	
• Performed before or at 90% of project completion. • Conducted by the Districts on all projects. • Results sent to Frankfort and Lessons Learned Database.	• Bring in-house personnel to conduct post construction review that should include project manager, consultants, resident engineers, general and sub-contractors. • Have multiple post construction reviews if feasible.

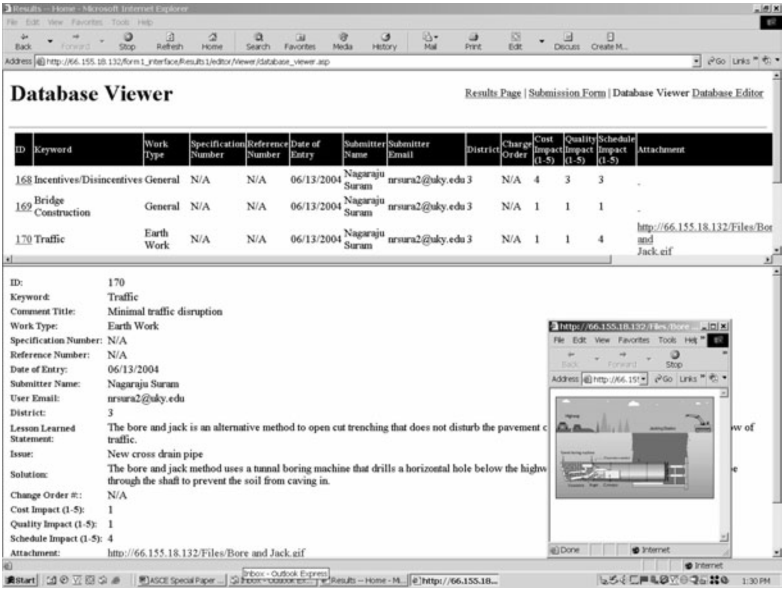

Figure 2. Cabinet's lessons learned system

The Cabinet's Lessons Learned System is an Internet accessible database that accepts both text and multimedia data. Although described in detail elsewhere (Goodrum et al. 2004), its purpose it to capture lessons learned on all projects and to make that information available to current and future project participants anywhere and anytime. In addition to identifying recurring issues, the Lessons Learned System is a tool that can be used to track recurring issues on roadway construction projects and identify practices that need to be changed within the Cabinet to avoid their reoccurrence.

Summary and Conclusions

A constructability review process, with procedures similar to those presented here, provides three general benefits. First, improved constructability of projects will improve jobsite productivity. Second, enhanced teamwork and communication early in project development leads to more cost effective design and construction, and third, more effective sharing of lessons learned occurs between projects.

This research found that time, available manpower, experience, and contractor reluctance were four categories of barriers to most constructability review programs among transportation agencies; whereas, traffic control, existing utilities, geotechnical, ROW, bridge structures, and new utilities are some of the common constructability issues encountered on Cabinet projects.

The constructability review process should be started at the same time that the initial project planning starts in order to maximize the potential benefits. This is achieved when persons with construction knowledge and experience become involved at the early stages of a project's development. The amount of involvement depends on the type and complexity of the project. A post construction review, or reviews, is also a valuable part of the constructability review process.

In conclusion, a constructability review process, whether performed in-house or by an independent third party, will help minimize conflicts, ambiguities, omissions and change orders, improve competitiveness in bidding, and reduce the possibility of legal problems. Constructability review processes can significantly enhance the achievement of project safety, quality, productivity, schedule, and cost. In short, a constructability review process assures that contract documents are biddable, and that the project is buildable at a reasonable cost, within a reasonable amount of time.

Future work is still needed to help resolve and avoid constructability issues from reoccurring as well as knowledge regarding the effectiveness of current efforts. First, there is undoubtedly a tremendous benefit to be gained if STAs across the United States could share their constructability lessons learned. There is currently no central repository for this type of information. A national database of this knowledge that would allow STAs to share and query for lessons learned would help meet this need. Second, the costs of recurring constructability issues on STAs are not known. As shown by others (Dunston et al., 2002), the economic return for conducting constructability reviews can provide substantial savings to project stakeholders. Additional research that quantifies the economic benefits on a large scale could provide the evidence and motivation needed to stimulate more STAs to incorporate a comprehensive constructability review program in the project development process.

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Effective Enterprise-wide use of Lessons Learned – Specific Experience in the Project Design Environment

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Abstract

For an extended period of time, the importance of the collection and re-use of lessons learned enterprise-wide has been recognized. In most all cases, however, attempts to place a self-sustaining lessons learned methodology within an organization have failed. After a review of prior attempts, the authors identified the keys to a successful design to be: the capture of potential lessons and reuse approved lessons within the appropriate legacy system, a formal vetting process, and a lesson retirement (sunsetting) process. This paper presents both the necessary architecture for a successful lessons learned system as well as the observed experience in fielding such as system enterprise-wide to support project development.

Introduction

A cursory review of stories in the public media as well as those in trade and professional publications for articles related to "lessons learned" demonstrates a current acknowledgement of the need to not repeat mistakes made in the past. While this is a noble goal, the ability of those in the future to access and apply the lessons we learn today is not as great as we would like. Historians often have some ideas of lessons learned in the past, but are often unable to put these forward and expose them effectively to the public. Licensed professionals and academics have a variety of ways to keep current on new issues through publications and through peer interaction. Most professionals, however, are subject to substantial time constraints and therefore have to base decisions on limited personal professional knowledge rather than to seek help from other sources.

A pattern related to lessons learned (a lessons-learned regarding lessons-learned) identified by the authors after study of a several efforts indicates that while the political will is high, such as after a major problem/disaster, decision makers do

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spend considerable effort to address the capture of lessons learned. Lessons-learned bureaucracies are often created to accept and publish lessons learned. Over time, the expense of these bureaucracies, combined with lack of tangible results from these lessons-learned activities resulted in the demise of these activities. In some situations these bureaucracies become self-serving, self-sustaining activities whose members maintain lessons learned for the benefit of their own internal community.

Objective

The objective of this paper is to identify the contents of and requirements for an effective lessons learned business process. A software implementation that enables this process is described. The costs and benefits of such a lessons learned approach are also identified.

Definition

Lessons learned are often described in many ways such as "...usable content that can benefit targeted organizational processes" (Weber et al. 2000), or "...a set of rules or principles that summarizes past experiences in such a way that helps the origination team perform its future task better" (PERTAN Group 2001). These and other definitions refer to the term "lessons learned" as an identified issue that resulted from detrimental events. Such a definition limits the perception of the type of information that could support future good decision making. In this paper "lessons learned" refers to repetitive deficiencies, good work practices, and success stories. This broader definition includes both positive and negative experiences both of which are important organizational experiences.

Another dimension of lessons learned pertains to the nature of the lesson. The majority of lessons refer to specific technical items that can be described in several sentences. This class of lessons lends itself to codification using a people-to-document approach (Hansen et al. 1999). The second class of lessons learned covers the more complex issues related to organizational relationships and business processes. This class of lessons is rich in context and much more difficult to capture, evaluate, index against database pointers, and distribute due to the personal expertise-specific nature of the subject. These types of lessons are best described in a scenario based (sometimes referred to as a story telling) environment, such as would occur within a mentor-protégé setting. An excellent example of these types of lessons is the identification of market opportunities for smaller sized disk drives which is discussed by Clayton Christenson (2003) and the development of a market for various types of soap (Dryer et al. 2004). The focus of this paper is on lessons that lend themselves to codification and therefore can be most efficiently used within information systems available today.

Focus of Paper

The concepts presented in this paper relate to the experience gained during the past 10 years of developing an operational system to support capture, vetting, and reuse of lessons learned within the design and construction arena. Highlighted are a survey of the state of the practice, successful design parameters for a lesson learned system, adoption issues, and economic benefits from re-use of lessons learned gained from providing automated tools to support capture and reuse of knowledge to thousands of users over the past ten years.

Lessons Learned Failures

In the 1990s many corporations and federal agencies, beyond consulting entities, began to recognize that the new economy was an information age and it was replacing the current industrial age. With this realization it became widely recognized that a significant organization resource was the corporate knowledge accumulated by its employees and there was a need to efficiently capture and distribute this expertise across the organization. During this time frame such terms as knowledge worker, knowledge management, and lessons learned (LL) became widely used and a variety of approaches under each topic were implemented to capitalize on this unique organizational resource.

The initial approach with most of these methodologies was to create a stand alone database into which LL information was placed with various indices to allow efficient retrievals. This approach was time consuming, quite costly, and unfortunately not effective for three important reasons:

1. *Not linked to End User*. The key reason that attempts to centralize lessons learned to date have not been successful is because users are unable or unwilling to access central 'knowledge stores.' Previous attempts to develop distributed systems have resulted in system designs that lack long-term sustainability for a variety of reasons: they tend to be championed by a limited number of individuals, they typically have a different interface and access structure, and they are difficult to locate and access by remote "possible users". Probably the most significant reason for failure is that the LL repositories are not linked to or embedded in the end-user application that would most benefit from this knowledge. This view is supported by Davenport and Glasser, who stated "While there are several ways to bake knowledge into knowledge work, the most promising method is to embed it in the technology the knowledge workers use to do their jobs (Davenport and Glasser 2002). A stand alone approach requires a user to stop what he or she is doing, do what is necessary to locate this LL repository, gain access to the system, and craft a retrieval query. This is clearly not "just in time" information delivery and this "disconnected" information is, therefore, rarely accessed.
2. *LL entries are typically not vetted.* Most approaches to capturing LL are centered on consolidating as much knowledge as possible from as wide a spectrum of subject matter experts as possible. Often the LL gathers are not subject matter experts (SME) but are database programmers. The inherent problem with such an approach is that database entries are not vetted and hence vary in terms of conciseness, quality, applicability, and

breath. Typically the end product of these "collection" efforts is a large quantity of poorly organized data with limited usefulness. In most cases, the level of success of the effort is judged in terms of the number of entries in the database. What is often overlooked is the fact that if the source of information has limited usefulness, end users will not invest the time necessary to use the information. Some firms have recognized the need to vet entries. Ernst and Young have a staff dedicated to coding information in approximately 40 "practice areas" (Hansen et al. 1999). Xerox had an aggressive vetting process for copy machine service suggestions to ensure that what was distributed was relevant, reliable, and not redundant (Brown and Duguid 2000).

3. *LL entries are not retired (sunsetted) when they are not longer valid.* Stand alone databases maintained by a limited number of individuals (often one or two) typically don't have a process or method to review and sunset content that is no longer valid. Out of date information is a clear marker to a user that this site is not be visited again.

Lessons Learned System Requirements

The experience by the authors and others is that a successful LL system must have the following three basic design elements:

1. Any LL repository must be directly linked to the legacy application that would benefit from this knowledge. This linkage should include a similar user interface, a common data indexing, and the ability to not only retrieve LL, but also to capture potential LL.
2. A potential LL should be vetted by subject matter experts before they are classified as a LL. The submitter should be kept informed of the review process and be able to respond to evaluator inquires should the content of the submitted LL be unclear to the evaluator.
3. A formal retirement process must be a feature of any LL system to keep the content current. This function should be the responsibility of the LL evaluators. Since they are familiar with the subject matter and may also be involved in a business process change to remove the need for the LL. Within the construction project design quality LL process, typically many LL spawn a criteria change request. Once the construction criteria have been changed to solve the LL issue, the need for the LL no longer exists and the LL can be retired. This sunsetting process must be built into any LL effort to keep the content of database current and useful for users.

Effective Corporate Lessons Learned System Design

In a large and distributed organization, such as the Corps of Engineers, similar projects are often completed by various teams composed of individuals with different historical experience levels. As a result, lessons learned by one team are often not readily or easily available to other geographically remote teams and must be relearned at many sites. Without effective communication methods, recurring problems are inevitable because although different project teams must deal with a variety of customers and locations, there are many repetitive project types and project designs that occur within a large organization such as the Corps of Engineers. By building an effective lessons learned sharing and use mechanism into users' daily business process, repetitive problems will virtually disappear because the correct solution to the current problem can be easily identified.

Allowing customers to participate in the identification of customer and location specific criteria will strengthen the bond between the service or product provider and its customers. The authors' initial focus of developing a Corporate Lessons Learned (CLL) approach was to address the topic area of design quality within the Corps of Engineers. Hence this application was titled the Design Quality Lessons Learned (DQLL^{sm}). However, the CLL concept as described below can and should be used with any business process and is designed so it can collect needed information vertically or horizontally across staff efforts or line activities.

Several key initial CLL design requirements were established: (1) a local capture and reuse capability should be easy to add to any existing legacy software application; (2) data transmission and communication would be via the World Wide Web; and (3) the design should be such that no or minimal firewall issues should occur when the information is shared across enterprise boundaries.

In the CLL system, the "LL Registry" is the sharing mechanism that allows employees to quickly find lessons learned repositories across a distributed organization's knowledge stores that relate to their current problem issue. The Registry is the worldwide address book that identifies the locations of all repositories on all LL topics. This concept is of local lessons entry from an application, such as the Design Review and Checking System - DrChecks^{sm} (1), local lesson approval (2), and retrieval by the Registry (3) is portrayed in Figure 1 below. Note that local pending LL topics that are of a headquarters/national (or organizational-wide) level should be concurrently submitted for organization-wide vetting (4) by a separate subject matter expert. The content of organization-wide LL would tend to be more general and not as specific in regards to customer or location specific issues as LL that are developed at regional offices.

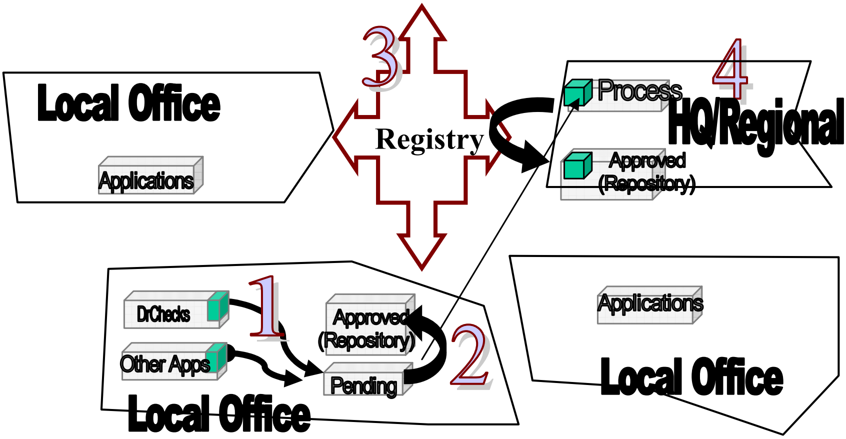

Figure 1. Lessons learned design

Subject Matter Repositories

The distributed architecture described in Figure 1 allows a multiple number of repositories each of which is tailored to the specific business application it primarily services. The relationship between the indices is maintained within the Registry and will allow seamless searching across repositories for common or complementary data elements even if they are indexed against varying descriptors. For example, if a legacy design review application, such as DrChecks^{sm}, uses the term Cost Engineering as a discipline for indexing design review comments within the Design Quality Lesson Learned Repository and a legacy construction field office application stores cost lessons within a Field Office Lessons Learned Repository against a disciplines of Cost Estimating or Estimating, the Registry will be able to map between these differing indices and retrieve lessons in either direction (from the Field Office repository to complement the Design Quality lessons or from the Design Quality repository to complement the Field Office lessons.

Linkage to Legacy Systems

The authors have found that the key to successful LL system is to link it to existing legacy applications. The specific application that DQLL^{sm} is linked to is the Design Review and Checking System (DrChecks^{sm}) (ENR 2002). This web-based software application radically improves the execution of the design review process. All business partners are linked via the web which allows near real-time collaboration (East et al. 2004). Specifically, any participant in a design review process can enter a comment from any location via the web. Once a comment has been posted it can be reviewed by a screener if necessary before it is responded to by the designer. The original submitter or another individual can backcheck the designer's response to determine if the action proposed is correct and complete. All participants have accesses to a wide variety of reports that provide detailed information about the progress towards resolution of every comment that has been entered. Comments that impact time, cost, or scope can be flagged by the evaluator and are easily retrieved by project manager for review and resolution. The process is shown diagrammatically in Figure 2.

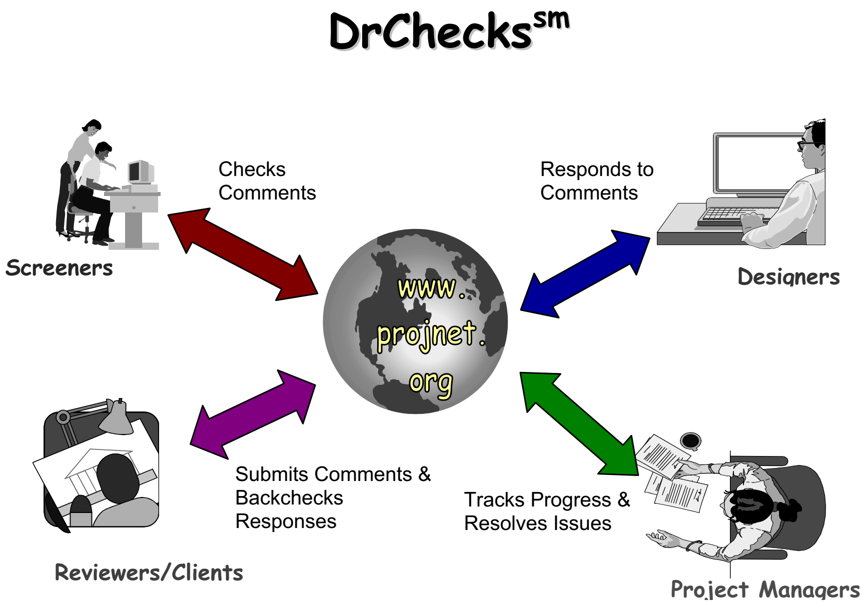

Figure 2. Comment process with DrChecks^{sm}

As previously stated above, the effective use of a lessons learned application requires that it be integrated with the legacy application that it can both generate as well as reuse lessons learned. DQLL^{sm} is linked to the comment entry process within DrChecks^{sm} as is shown in Figure 3. If during the comment entry process an individual believes the comment topic might be the basis of a lesson learned, the commenter only has to press a single button to capture the comment and all of the project index information. This information, along with any possible solution the submitter has to offer, is automatically emailed to a pre-identified subject matter expert (SME) for evaluation. Depending upon the nature and scope of the proposed lesson learned, the submission could be evaluated by a local SME or a national (or enterprise-wide) SME. Both the submitter and the SME receive confirmatory emails that a potential LL has been sent for evaluation. If the SME deems the submission a valid LL, the SME "approves" the LL and it then becomes posted to the DQLL^{sm} database and is then retrievable for re-use.

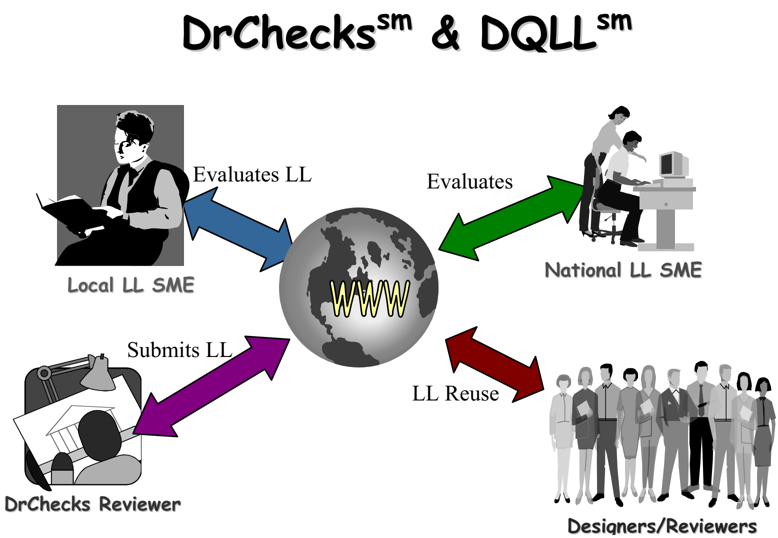

Figure 3. DQLL^{sm} submission, evaluation, and reuse procedure

By design, DrChecks^{sm} has a search feature that allows a comment submitter to query past comments or LL's that might apply to the design currently being reviewed. Advanced search routines allow targeted searches against specific discipline, project type, location, or key word. The search results are presented in a tabular form and have a check box which will copy the retrieved comment or lesson learned into the current review as a comment. Editing of the imported comment or lesson allows tailoring of the information for the specific circumstance of the design issue being addressed.

Experiences and benefits from the use DQLL^{sm}

An earlier evaluation of the economic benefits from LL capture and reuse within the Corps of Engineers found that net average savings from 29 lessons that were captured and vetted was $23,000 per lesson per single Corps of Engineers district reuse (Kirby 2002). These findings were calculated from a detailed evaluation of savings offered minus the cost of implementing the lesson learned. The lesson collection and vetting process has been shown to be an effective method as only a small fraction of comments become actual approved lessons learned (on the order of 0.3%). The DQLL^{sm} SME's are typically identified by discipline although any comment index item can be used to route a submitted LL to a SME (customer, project type, location, or another index item). This small sieve evaluation schema is the intent and goal of LL collection and vetting proposed in this paper since most design review comments don't meet the requirements of lessons that relate to repetitive deficiencies, good work practices, or success stories that are not covered by construction criteria or standard practices. The relatively low number of comments that are chosen by submitter to be forwarded as potential LL, means that the time required to be an organizational SME is not great and generally will not impact the time available to accomplish his or hers normal assignments.

Since the time of the performance of the DQLL^{sm} economic evaluation, the Corps of Engineers has adopted DrChecks^{sm} enterprise-wide. Since DrChecks^{sm} serves as the backbone for LL collection and reuse, the benefits from only one district now have a multiplier of 43 (the number of district equivalents using DrChecks^{sm} within the Corps of Engineers). Now lessons approved in the Seattle District are available for reuse throughout the United States and also at overseas Corps of Engineers locations.

Lessons Learned on the Adoption Rate of DQLL^{sm}

The initial development effort was to demonstrate the benefits of linking a lessons learned system with an operational application. Hence DrChecks^{sm} was actually developed to demonstrate DQLL^{sm}. Both applications were initially developed in 1998. The authors were surprised that DrChecks^{sm} was rapidly adopted by design professionals within five (5) federal agencies but the DQLL^{sm} adoption rate was much slower. This differing rate of diffusion of these innovations (Rogers 1995) was unexpected by the authors. At the onset it was felt that decision makers of adopting agencies would see the merit of both applications and adopt them at an equivalent rate. Several early adopters of DQLL^{sm} have required all A/Es to certify that they have reviewed the DQLL^{sm} lessons and have incorporated those that are appropriate to the current project.

It appears that enterprise-wide however, a phased adoption strategy is most likely the one to be followed. The initial requirement is that the legacy application should have a wide user base and be fully integrated into the organization's business processes. Once the legacy system has reached "business as usual" stage, the organization decision makers will be more likely to consider adopting a LL enhancement.

A majority of the Corps of Engineers districts are now just beginning to adopt DQLL during the 2004-2005 time-frames. DrChecks^{sm} use within the Corps of Engineers was mandated in 2001. The comment submission growth of DrChecks^{sm} was quite large until 2004 when the Corps began reaching a steady state rate of use. Figure 4 demonstrates the number of comments entered by Corps of Engineers users of DrChecks^{sm} during the period 2002-2004.

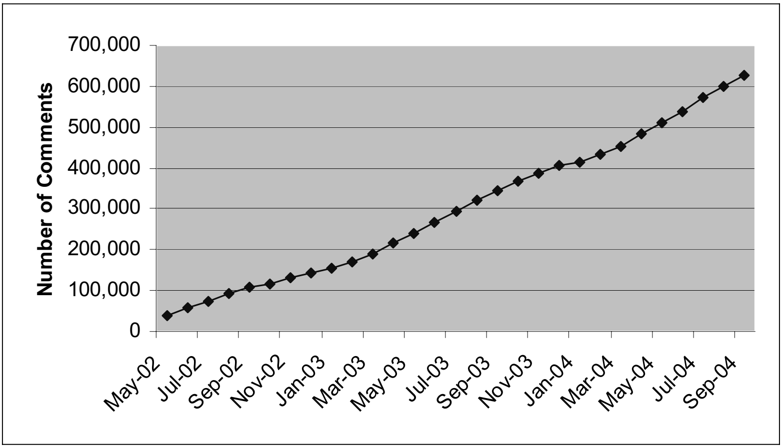

Figure 4. DrChecks^{sm} comment entry by the Corps of Engineers

While Figure 4 does show a constant dramatic growth in the number of design review comment entered in DrChecks^{sm}, what is more telling is the rate of change of comment entry over time. Figure 5 shows a steady state of comment growth was reached in later 2003. At that period of time DrChecks^{sm} was almost fully implemented at all 43 district and center offices. Comment growth rate can be shown to have reached a more or less steady slope by 2004.

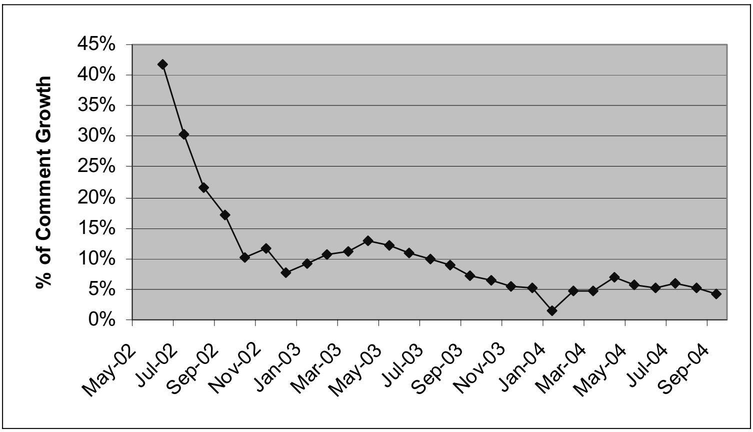

Figure 5. Rate of DrChecks^{sm} comment submission growth

While DQLL^{sm} has been available for use within the Corps of Engineers since1998, it is only within the last year that an organizational-wide interest has been demonstrated. In 2005, 17 of the 43 Corps of Engineers districts have committed to use DQLL^{sm}. The other five federal agencies have not adopted DQLL^{sm} at this time. Lesson entry has begun and is expected to continue to increase as the early DQLL^{sm} adopters become fully operational in 2005. Figure 6 displays the observed LL approval rate within the Corps of Engineers.

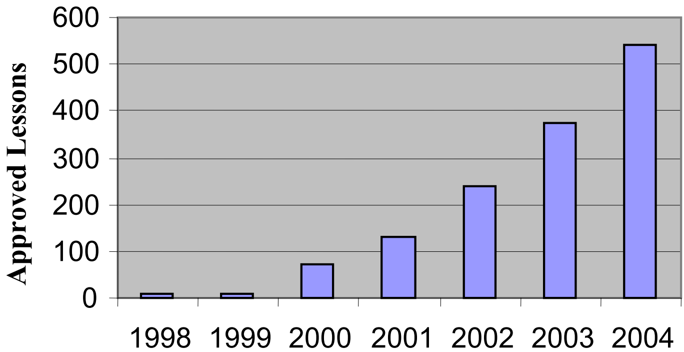

Figure 6. Growth in lessons learned approved in DQLL^{sm}

Future Lessons Learned Development Efforts

The authors fully expect that DQLL^{sm} implementation within the Corps of Engineers will continue to grow during the next few years. It is also expected that other agencies using DrChecks^{sm} will see the merit of expanded use and will require DQLL^{sm} to be more fully integrated into other related legacy systems.

We have recently linked the DQLL^{sm} approval process to several other tools within the www.projnet.org design quality suite that manage the criteria for the Corps of Engineers as well as the Navy, NASA, and the Air Force. Now, if during an evaluation of a proposed LL the SME determines that the solution to this issue is a change to an existing criterion, the SME can automatically route the proposed LL to the appropriate criteria manager as a Criteria Change Request (CCR). The CCR is a web process that replaces a paper form that is used to take an extended time period to reach the party responsible for managing their criteria. The CCR program notifies the individual responsible for the criteria that a change request has been posted and also informs the submitter (in the DQLL^{sm} submittal process this is the DQLL^{sm} SME) that the change request has been emailed to the responsible party. CCRs can also be directly submitted on www.projnet.org by any party (even one without a login). A secondary program, the Criteria Management System (CMS), maintains detailed information about all of the criteria (age of document, responsible party, agency proponent, and number of CCRs submitted against the criteria). Specialized CMS reports help criteria managers decide which and when criteria will be updated. A third linked program, Standards and Criteria Program (SCP), assist with the management of the funding of criteria update activities. Thus, the process of updating criteria based upon lesson learned submittals is now seamless from proposed lessons learned entry through resolution via a criteria change. Once the criteria has been updated, the SME can sunset the DQLL^{sm} issue as it now has been resolved via an updated criteria. The above process is shown in Figure 7.

The authors also feel the next local extension to DQLL^{sm} is the addition of a push technology that would prompt the user that an approved LL existed for the topic the individual was addressing. The approach will to have a DQLL^{sm} search or data mining routine run in the background while a DrChecks^{sm} user is entering a design review comment. The user will be able to specify how wide or narrow the scope of lessons he or she desired to be presented for review. The authors believe this would be "killer (desirable) application" that would drive a quick DQLL^{sm} adoption rate.

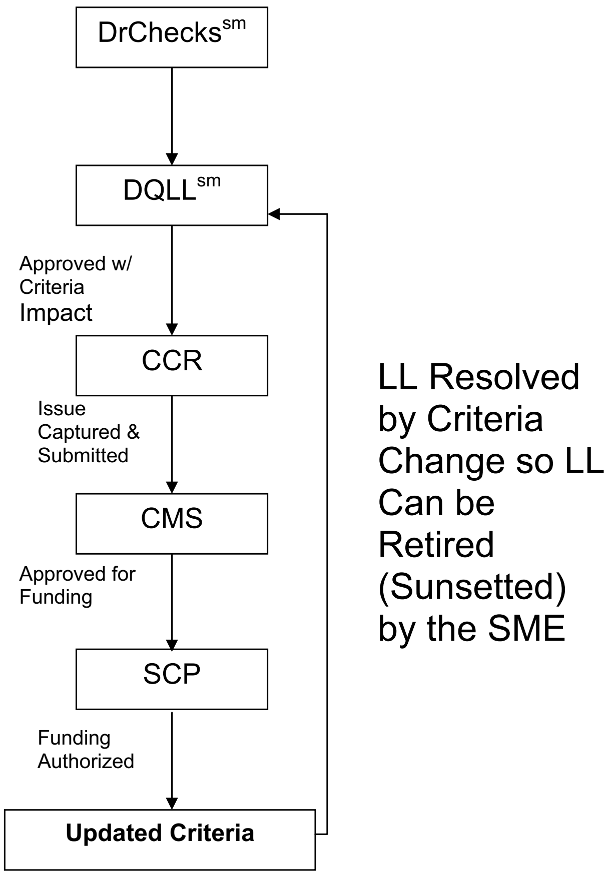

Figure 7. DQLL^{sm} issue resolved by criteria change in ProjNet^{sm}

Conclusions

There is a definite positive economic consequence from the capture and reuse of lessons learned across a wide range of business processes. Successful lessons learned system can be completely implemented if the application is fully integrated within the legacy system it supports, it contains information that is vetted by subject matter experts, and the lessons are retired when they are no longer appropriate.

Searchable lesson learned repositories offer professionals the ability to gain and reuse knowledge of other geographically remote experts. While the above has been show to save the Corps of Engineers an average of $23,000 per reuse of a design lesson, lesson learned repositories can also allow the programmatic review of problem areas. Analysis of the number of lessons per indices (i.e. design discipline, reviewer, designer, location, or customer) may point to a systemic issue that may require exploration and resolution.

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Using Transportation Construction Contracts to Create Social Equity

Sarah Picker[11]

Abstract

As owners, designers, and constructors, how do we implement and succeed with non-project goals as social equity – as requirements to include disadvantaged business enterprises goals in construction contract bids – in our projects? This question applies to the discussion of constructability.

One social equity pubic policy is to include historically excluded businesses in construction work to benefit them and to redress past inequities. These objectives for social equity are achieved in various mechanisms throughout the design-bid-build project development process. This paper concentrates on the construction contract as a specific mechanism to achieve policy. Inevitably this must involve owners, designers, and contractors/constructors. Also, marketing and community planning efforts that the owner and constructor can implement are discussed, the outcome of the efforts ultimately being reflected in more bidders meeting contract DBE goals.

Introduction

According to the definition adopted by the Constructability Committee within the Construction Institute of the American Society for Civil Engineering (ASCE), "constructability is the integration of construction knowledge and experience in the planning, design, procurement and construction, operation, maintenance and decommissioning phases of projects consistent with overall project objectives." This definition was presented by James Pocock et al. and included in their paper entitled "Constructability State of Practice Report" (2004).

Since most projects are built to accomplish civic, economic, safety, and social goals through construction related jobs, the definition considerations for constructability must include such objectives as sharing employment and targeting jobs to communities that have historically been excluded. When discussing constructability, one must pay attention the procurement of the construction contract as a practical method for achieving public policy goal of valuing social equity. The bidding process can help achieve the objective of social equity because the contract is

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the legal mechanism that require project to include disadvantaged business enterprises (DBE's) during construction project.

This paper uses transportation projects as examples; however, the marketing concepts discussed herein could apply to any type of infrastructure project where the owner and constructor must consider requirements for job stimulation in a DBE community.

Construction Contract

Public agencies (owners) function such that the project is designed by the owner and advertised for competitive bidding in the construction market, the lowest bidder being the company that builds the project for the owner. Public contract law was drafted to protect taxpayer funds from fraud and abuse and to provide for fair and efficient administration of public works contracts. In California, the set of rules used to govern how the process is implemented is called the Public Contract Act.

This Act and subsequent sets of regulation place responsibility on the public agency for proper preparation of the construction contract or bid documents. The ASCE Constructability State of Practice Report indicates that constructability should consider whether the construction contract documents are biddable.

Projects that are biddable are fully designed with 100% complete engineering plans and specifications and the engineering estimate. The estimate is an accurate representation of current anticipated costs for all items of work that are included in the plans and specifications. The bidding process is a competitive bidding process and contracts are awarded to the lowest bidder, pending an assessment that they met the contract requirements. They include insurance, bond, financial requirements and meeting DBE goals.

The United States Department of Transportation seeks to solve social equity issues through the implementation of Federal Regulations 49 CFR Part 26, amended June 16, 2003. This regulation requires that construction contracts for transportation capital projects must contain provisions that a percentage of the contract dollars are to be subcontractors (or suppliers, or manufacturers or trucking operations) designated as DBE firms. This rule was promulgated in 1999. The federal register discussion preceding the regulations states: "The DBE program is intended to remedy past and current discrimination against disadvantaged business enterprises, ensure a level 'playing field' and foster equal opportunity in DOT-assisted contracts" (Federal Register 1999).

A high percentage of transportation contracts being implemented at state, local or a special district levels use federal monies and are thus obligated to comply with federal regulations. The public transportation agency/owner must enforce these provisions. Therefore the contractors who build transportation projects must consider the federal contracting requirements for DBE firms when bidding on contracts. The owner must also be involved and knowledgeable and active in the contracting market to ensure that DBE companies know of potential projects and can meet federal requirements as specified in the construction contracts.

The low bidder has competed to be the constructor. In the competition process, public agencies are not given unfettered discretion to award bids, meaning they must award to the winning low bidder. During the performance of contract, contractors are held to exacting standards of performance once the job is underway. At bid these are also exacting standards. The lowest bidder is the winning bidder only if they meet all the requirements of the contract, including contract special provisions that related to social equity.

These criteria are applied by the owner when considering whether the bidder has met the contract, which indicates responsiveness or responsibility; that is whether the constructor has met the DBE goal. Can the low bidder show that the percent specified in the contract will go to DBE companies? Table 1 shows several Caltrans projects where the DBE goals have been met.

Table 1. Caltrans projects containing DBE goals

Owner	**Project**	**Contract set DBE goal (%)**	**% DBE achieved in bid**	**Contract type**	**Total contract amount at award ($)**	**Commitment towards DBE goal at award ($)**
Caltrans	Hwy. 99	12.00%	12.30%	6 miles highway widening including two overcrossings	$15,439,966	$1,899,000
Caltrans	SFOBB	16.00%	36.30%	YBI USCG Road Relocation	$1,512,300	$548,965
Caltrans	SFOBB	8.00%	9.46%	W2 Foundations	$24,083,285	$2,278,279
Port of Oakland	OIA	8.00%	8.00%	Aircraft Sound Insulation Program	$10,929,481	$8,743,000
Port of Oakland	OIA	9.80%	16.00%	Reconstruction of Taxiway D and Apron Improvements Adjacent to Building L-812 North Field	$5,069,783	$811,000
Port of Oakland	OAI	11.00%	16.64%	Construction of Asphalt Concrete Overlay of taxiway A East of Taxiway B, North Field	$454,310	$76,000
Port of Oakland	OIA	7.70%	36.24%	Reconstruction of East Apron-Phase 1 South Field	$12,566,465	$452,000
Port of Oakland	OIA	8.10%	9%	Runway Safety Areas (RSAs) Studies at Oakland International Airport	Not reported	Not reported

Considerations for Constructors and Owners

The transportation agency, designer, and bidders should implement marketing and community planning efforts to contracts meet DBE goals, i.e. encouraging contractors to commit to using DBE's in the construction contract. Owners should strive to ensure active DBE participation by community planning efforts and marketing like networking, gathering lists, knowing local availability, knowing how to contact groups and interact regarding bidding. Such activities should occur continuously as a standard business practice. Then, when a contract is ready to be bid, owners and constructors will have the necessary knowledge of DBE availability and capacity.

The definition of a Disadvantage Business Enterprise is from federal regulation 49 CFR Part 26. A Disadvantaged Business Enterprise (DBE) company must meet three basic eligibility standards:

1. They must be a small business;
2. The firm must have at least 51% ownership by a disadvantaged owner; and
3. Disadvantaged owners must exercise 51% control over daily management and operations.

A DBE company's average gross receipts for the past three years must not exceed $17,420,000 for General contractors, $7,000,000 for Specialty contractors, and $4,000,000 for Engineering, Architectural, and Surveying firms. For other specialty areas the standards of Small Business Administration apply.

The following types of firms are examples of DBE companies with abilities to bid on transportation projects: electrical contractor, field office setup contractor, suppliers, rebar, environmental and vibration monitoring, temporary construction works, engineering consultant, inspection services, fuel supplier, computer graphics engineers, reproduction services. Depending on the contract estimate, certain DBE construction firms could also qualify to be a prime bidder.

The timeline for implementing specific activities is based on advertisement and bid due dates and is intended to develop tangible subcontracting opportunities. Each construction contract is unique, and efforts to bring DBE's into the bidding process should occur several months before bid within this timeframe the constructors will have the opportunity the plans and specifications and consider which work they can sub-contract out.

The community planning and marketing programs should assist firms in the process of being able to compete successfully in the market place, remove barriers to the participation of DBE's in projects, and create a level playing field on which DBE's can compete fairly for contracts. Such programs can also encourage partnerships between the prime contractor and smaller local sub-tier contractors. An example would be to attend and participate in conferences such as the U.S. Department of Transportation's Minority Resource Center Regional Conference for Disadvantaged Business Firms which took place in June 2005 in Oakland, California.

At the first National DBE conference held in Washington in November 2004, Secretary of Transportation Norman Y. Mineta stated that the U.S. Department of Transportation (DOT) will strengthen its commitment to the owners of Small, Minority, and Women-owned, Disadvantaged Businesses by helping them obtain capital, training, and other assistance in order to promote their participation in the U.S. transportation industry. This led Secretary Mineta to authorize the Western Region Minority Resource Center (MRC) to host its DBE Economic Summit/Conference. Kaye Stevens, President and CEO of Anue Management Group which operates the Western Region MRC, has established a planning committee with participants from public transportation agencies including BART, Port of Oakland, and Alameda County Transit Improvement Authority, as well as Alameda County General Services (GSA), community organizations, and representatives and small businesses.

This western region conference benefits Disadvantaged Business Enterprises, prime contractors (constructors), and DOT agencies/grantees from Arizona, Nevada, and the entire state of California. There were workshops, a plenary session, a luncheon, and a class by the eminent Dr. Dennis Kimbro. The mission of the summit was to bring IT software, finance opportunities and access, business training, and procurement opportunities to DBE's. The workshops covered estimating and bidding, project management, job costing, and construction accounting. Participants learned about the U.S. Department of Transportation's Short Term Lending Program (STLP) and networked with bankers, buyers, prime contractors, corporate businesses, and agencies on the federal, state, and local level. Dr. Kimbro's class was about business practices, management, entrepreneurship, and economics.

Attending these meetings allows construction firms to become familiar with DBE firms. Constructors can better track the DBE market for capacity and services; the can also gather information such as lists of plan holders, certification lists, and advocacy group memberships and meeting sign-in sheets. Also, the constructor can learn about short-term lending programs sponsored by the U.S. Department of Transportation which help solve cash flow problems for small companies. The federal government has created bond and loan guarantee programs to support loans and bonds for small businesses which could not otherwise obtain financial instruments and guarantees. When a project is completed and loans repaid, the guarantees are released and the trust fund becomes available for future guarantees.

Owners should inform the construction market about projects. They can organize meetings specific to each construction contract or set of contracts to market DBE opportunities and provide a networking forum. At the meetings, owners can inform designers, constructors, and DBE's of the contracting opportunities for specific construction contracts. Invitees should include local minority business organizations.

During the networking portions of meetings, the owners should make an effort to see that DBE's can obtain information about the process of participating in the contract bidding. Information tables manned by owners and other transportation related programs can show how DBE's can participate in the bidding process.

To meet DBE goals, Mr. Ed Dillard suggests that constructors make an effort to involve and inform DBE's about construction contracts and provide information on how to submit bids for their firm's consideration (Dillard 2004). He also says it may also be necessary to provide DBE's access to information relevant to the project and bidding process such as plans and specifications or historic cost information.

Dillard suggests that the owner and constructor should match work items from the contract that could be subcontracted to a DBE firm. Also, any work known to be subcontracted to a first or second level subcontractor could be subsequently contracted to DBE's. Based on subcontractable work items, owner, constructors, and lower tiered subcontractors should research local firms' availability and explore all tangible opportunities.

Another suggestion by Dillard is that the constructor should look for DBE companies listed in directories by cities, transportation agencies, chambers of commerce, and trade associations. Transportation programs subject to the federal requirements have listings of DBE's. Often this information can be accessed on line. One logical place to start is at the Federal Highway Administration website (www.fhwa.gov). Also, a local minority chamber of commerce or professional association will have information on its members' capabilities.

Dillard also produces a television program, "Bay Area Business Today", that is shown on a cable local access station in Oakland, California. One segment highlighted an outreach effort by the Port of Oakland, one of the successful owners shown in Table 1.

Once identified, these DBE companies should receive written solicitation of bid opportunities. This solicitation should be sent well ahead of the bid opening date to ensure that the DBE can bid on the project in a timely fashion. Below is a list of the essential information that the constructor should provide to DBE in these solicitations:

- the name of the project,
- location of project,
- bid date,
- items of work available for the DBE to bid and construction contract scope of work,
- a location where they can review the plans and specifications, and
- the contact name and phone number for bonding, insurance, line of credit, technical assistance, and other resources.

Constructors should follow up initial solicitation with DBE firms by documenting all telephone calls and keeping a fax log. Ultimately, this documentation could be needed if the DBE goal is not met and the owner needs to assess whether the constructor has taken steps to ensure that a good faith effort has bee achieved.

Another way that owners and constructors can inform DBE's of contracting opportunities is to advertise requests for DBE participation in trade association publications and newspapers and papers with ethnic focus.

What if the goal cannot be met? The constructors must document that they have made a good faith effort to meet the goal. This is a requirement of the contract bid terms. By fully using the above suggestions and keeping good records of marketing efforts, the constructor can demonstrate a good faith effort.

Conclusions and Recommendations

This paper has brought implementing social equity policies to the constructability discussion. It provides information about how owners and constructors can actively seek out ways to bring contracts opportunities to groups targeted by social equity policies. These topics should be considered when evaluating constructability.

The U.S. Department of Transportation, the Small Business Administration, as well as state, local, and special transportation programs all carry out and participate in DBE marketing and community planning events. Using their webpages to pursue information about DBE's can help owners and contractors to market contractor opportunities to DBE's.

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An Overview of Constructability Tools

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Abstract

This paper includes an overview of twenty-seven constructability tools. These tools can be used for implementing the constructability process or analyzing constructability on any project. These constructability tools are divided into policy/process-based tools (thirteen), modeling tools (ten), and technology-based tools (four). The technology-based tools include both graphical (CAD animation) and non-graphical (databases, analytical) computer models. All of these tools are then mapped onto a generic constructability planning process model for a typical project so that users can develop an implementation strategy with these tools.

Introduction and Background

Initial constructability studies conducted by the Construction Industry Institute (CII) contained basic constructability definitions and concepts (CII 1986) with little written about implementation and analysis tools. These were followed later by more formalized constructability approaches that included "how to" manuals and guides (CII 1993). These early guides contained general tools about the constructability programs themselves, such as program roadmaps, program evaluations, program barriers, and the beginnings of some program documents.

Additional project level tools were further identified and articulated in technical reports produced by the University of Wisconsin-Madison for the Wisconsin Department of Transportation (Russell and Swiggum 1994a; 1994b). Finally, these tools were categorized according to policy/process-based tools, modeling tools, and technology-based tools. These tools were reviewed and narrowed from over fifty original tools to the current twenty-seven discussed in this paper (Fisher et al. 2000). This selection process included an evaluation by domain experts of tool:

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1. maturity,
2. ease of implementation,
3. maintainability,
4. cost of implementation, and
5. impact on the constructability process (Anderson and Fisher 1996).

The Constructability Committee of ASCE's Construction Institute maintains a comprehensive on-line catalog of documents and articles that are designed to aid members of a project team in the implementation of constructability on their projects. This on-line document catalog is located at the following website: http://www.cecer.army.mil/pl/catalog/index.cmf?RESETSITE+ConstrucCommit.

A review of the 80 citations currently residing at this site indicates that only about 20% of these resources address constructability tools directly. The majority of these resources (55%) deal with processes and programs. The other citations deal with actual lessons learned (10%) and special case studies of specific industries or specific construction operations (20%). This paper summarizes the various project level tools that are included in the literature that are available to the project team for constructability implementation and analysis. Furthermore, the paper links these tools to a typical constructability planning process model so that the reader is able to know when exactly during the life of a project to implement these various tools.

Policy/Process-Based Tools

Tools classified as being policy/process-based are those that can be used by the project team to understand and communicate constructability. Policy-based tools are tools which control the way an organization performs its tasks. These tools rely upon planning processes. They provide guidelines that personnel can follow to accomplish their assigned tasks. These tools do not have physical substance, but exist as documents, methods, and concepts. Most policy and process based and modeling tools are common sense good project management processes. In a review of the Constructability Committee of ASCE's Construction Institute's comprehensive on-line catalog, these tools were not addressed in any individual citation. However, these tools are extremely important. Even though they may appear obvious as good project management practices and easy to implement, the following thirteen tools bear reviewing from a constructability planning perspective.

Policy and Objective Statements. This is a written and circulated document regarding the goals and objective of an organization. This document explains what, where, whom, and how an organization is to perform its day to day activities with regard to specific goals and objectives. This often is the initial tool with which an organization can use to implement a constructability program. This statement needs to address the following key items with respect to constructability:

1. statement of program goals for the organization,
2. indication of the level of management and corporate commitment,
3. identification of the corporate executive sponsor, and
4. ties to project-level implementation

The amount of detail within this statement can vary greatly from a simple guide to an exact step by step outlined procedure (CII 1993; Russell and Swiggum 1994a).

Constructability Team/Meeting Agenda. A team is a group of individuals within an organization which have a common goal or task. The constructability team should be a cross-functional organization which is put together to jointly solve constructability problems. To facilitate the use of teams there needs to be orientation and reorientation of the team member at predetermined milestones within a project's duration (refer to Figure 1). These meetings are critical when presenting overall project objectives. The agenda for each of these meetings should be predetermined yet not totally fixed. Each meeting should include an overview of the project objectives and a presentation of project policies. With the team orientation meeting, a team concept allows the expertise of each individual member to be shared with all group members. The team eliminates the barriers present among the different sections within the process. By focusing on a common goal there is no need to promote the self interests of any one area at the expense of another, unless it has an overall positive effect on the final outcome. Teams should be formed early within a constructability program and remain throughout the entire project with only minor changes of personnel, depending on the needs of the team. This team orientation is a requisite for constructability to have an impact. Figure 1 gives an example of a time line of team orientation meetings which provides the impetus for successful team work (Champoux 1994).

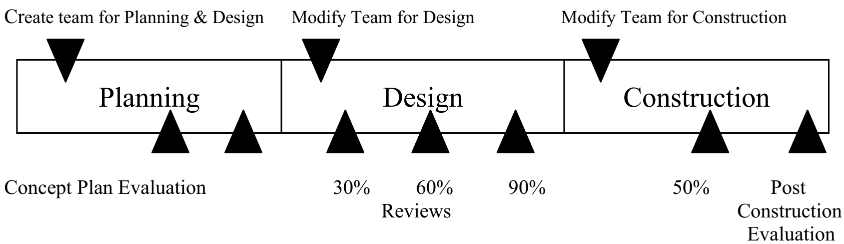

Figure 1. Constructability planning meeting plan (Fisher et al. 2000, ASCE)

Operations and Maintenance Input Checklist. Operations and maintenance personnel are the ones who inherit the finished product of the construction process. The operation and maintenance personnel benefit the most from well thought out designs and well constructed structures. They also suffer the greatest from the short fallings of design and construction. Therefore, it is necessary to design for ease of operation and maintenance (O&M). The O&M personnel should be involved in the earliest stages of design and have the ability to review the design prior to beginning construction in order to eliminate future maintenance or operational problems. Once a project is completed there needs to be a feedback loop to the designer from the operations and maintenance. This continuation of input from the O&M personnel regarding the long term performance of a structure is extremely important when the owner has many similarly designed structures. Many times feedback is possible only when the owner initiates the dialog and maintains the program throughout the use of the structure. One possible approach toward soliciting O&M data would be through the use of questionnaires (Russell and Swiggum 1994a).

Constructability Organization Structure. In order to get the most efficient use of knowledge from each phase of a construction project (planning, design, and construction), teams should be formed, which include the expertise of all phases of a particular project. This is accomplished through the use of an organization structure consisting of a matrix of authority and responsibility rather than the hierarchical arrangement found in many organizations. Each team member has responsibility for a particular project and the accountability to their section. These teams should be formed at the beginning of the project and remain intact throughout the project (see Figure 1), therefore giving each team member the responsibility over the whole project instead of only a small portion of the project. This project team approach will eliminate the barriers which are naturally present between the various disciplines of an organization. The team must be given a formalized structure in order to delegate responsibility within its members. With the proper organization team structure the teams will be self-managed where the members are truly empowered to organize their work and make decisions. These teams need to be identified in the initial stages of a project, allowing constructability input to be infused at a point where the greatest impact is felt. The project team organization structure initially consumes much more than it produces. An organization must be committed to the idea of making the initial investment for this approach to truly work (CII 1993; Russell and Swiggum 1994a; Champoux 1994).

Suggestion Forms. Suggestion forms are a way for constructability ideas to be collected throughout the project process. An illustration of this form is given in Figure 2 (CII 1993; Russell and Swiggum 1994a; Anderson and Fisher 1996).

Constructability Suggestion Form

Suggestion: ______________________________

Discipline/Craft Affected: ______________________________

Description & Illustration: ______________________________

Originated By: ______________________ Date: __________

Project: ______________________________

Assessment of Impact to Project: (to be completed by the Constructability Coordinator)

Cost: ______________________________
Schedule: ______________________________
Quality: ______________________________
Safety: ______________________________
Engineering: ______________________________
Need to change/update corporate standard specs? ______________
Other: ______________________________

Approvals: ______________ ______________

______________ ______________

Comments: ______________________________

____

Figure 2. Example of a constructability suggestion form (Anderson and Fisher 1996)
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Pre-Bid Conference Issues List. This conference is a meeting of all potential participants of a particular project prior to the submission of bids. A pre-bid conference is designed to get the flow of information from the owner to the contractor and vice versa. Prior to bid, all bidders are brought together and the owner explains the intent of the project and the intent of all documents and required programs. Any problems or ambiguities related to the project would be brought to the owners' and bidders' attention at the time. These conferences will clarify the project and eliminate unknowns and assumptions made by the contractor, thus removing some risk which will be reflected in the bid. Improvements in the design of construction are addressed and clarification on the roles of the responsible parties will be identified. This conference needs to be held early enough, prior to the letting of the bid in order to allow feedback from the conference to be received and incorporated into the project documents and requirements (Russell and Swiggum 1994a).

Pre-Construction Conference Issues List. This conference is a meeting between contractor and owner which is held after the bid is awarded. The objective of this conference is to resolve any unaddressed concerns of both the owner and contractor. This conference allows both parties to convey their intents and implement any new procedures and policies which will improve construction. The pre-construction conference should lay the framework for dialog throughout the project and provide a clear channel for constructability feedback.

Contract Incentive Clauses. The contract is the rule book as to how each party will perform. This instrument is used to create and enforce certain behavior. Certain contract clauses and incentives will provide the impetus for a constructability program to be used by the contractor and the feedback of lessons learned required from the owner. The use of the contract as a tool to implement constructability is very useful and powerful. These clauses force the desired actions regarding performance. Within the contract, the owner can specify what type of processes will be in place to improve constructability for both sides (CII 1993).

Partnering Agreements. Partnering is a program through which owners and contractors focus on developing a relationship which creates a project team united by a common mission and objective. The key elements of partnering include: commitment, trust, mutual advantage and opportunity. Partnering begins with a workshop being held at a neutral site prior to construction. During this workshop, which is facilitated by an impartial third party, representatives from each participating organization become acquainted. Within the workshop the participants:

1. identify obstacles to a successful relationship,
2. set goals for project and create a mission statement,
3. develop methods for resolving issues,
4. agree to time tables, and
5. assign responsibilities.

The use of partnering allows the knowledge to flow. Ease in obtaining information will eliminate the barriers present between the phases of the project. The use of partnering sessions will allow free flow of ideas and criticism which is needed for constructability. This will eliminate the adversarial positions which tend to develop between the designers, contractors and owners. In order for partnering to work there needs to be a development of particular behavior patterns based upon the attitude of trust and mutual respect. There needs to a commitment to the concept of team work for the total benefit of partnering to impact the project (Russell and Swiggum 1991a).

Contractor-Determined Schedules. The contractor is responsible for meeting the milestones of a project. These milestones are construction driven and are decided upon by having a desired project completion date, and the time to complete each required activity then working backwards to find when each activity much begin in order to meet the completion date. These schedules are more accurate if they are determined by the contractor. The contractor has a better knowledge of the times required by them to perform each task. These schedules are determined by the methods used by the contractor and the specific equipment available. The construction schedule would be submitted by the contractor prior to construction and approved by the owner. These schedules provide realistic milestones and proper sequencing of activities which allow the contractor and owner to accurately benchmark the progress throughout the project (Clough and Sears 1991).

Implementation Responsibility Matrix. A constructability issues matrix is a matrix that provides architecture for documentation of the lessons learned throughout a project which can be placed within the current working structure of the organization. This matrix allows all the lessons learned to be stored centrally and have their areas of application denoted. The matrix also allows for the status of each lesson learned to be monitored. This matrix requires all the individual sections of an organization to be listed. A second list is made of all the lessons learned for any particular project. A constructability issue matrix is formed when these lists are placed on perpendicular axis with the same origin. The areas of application for each lesson learned are noted by placing a mark at the intersection of the lesson and the affected area. A lesson learned can have more than one area of application (Russell and Swiggum 1994b).

Team Building Process. Team building is an organizational approach towards management which emphasizes the pooling of individual skills towards a singular goal. The strength of the team comes from the synergy developed between the members. The team development process consists of the following stages (Harris 1989; Russell and Swiggum 1994a):

- *Forming* – The forming stage is characterized by hesitation and the familiarization of the team members;
- *Storming* – The storming stage begins when team members begin to panic at the amount of work ahead and begin to brainstorm about possible approaches towards task completion;
- *Norming* – The norming stage is characterized by the group beginning to work together, rather than against each other. The roles played by each individual are assigned; and
- *Performing* – The performing stage is the final stage in which the team effectively works together toward the completion of required tasks.

Team building can be conducted during partnering for the constructability team and periodically up-dated throughout the project at constructability team meetings.

Constructability Engineering Role. In most large organizations, the more knowledgeable and experienced one becomes, the farther removed they become from the detailed tasks, and more managerial-type duties are required from them. The detailed designers and planners are typically the least senior and least experienced personnel. This situation requires an experienced and knowledgeable source for guidance and answers. This can be attained by using managers who specialize in the technical aspects of the organization rather than day to day management. Each main discipline needs a manager who is an expert in the field. It is this individual responsibility to keep the capabilities of their section up to standards by training and infusion of new technologies. Construction knowledge can also be provided by constructability engineers who are individuals who concentrate specifically on constructability issues of projects. Both of the positions of discipline engineer and constructability engineer require very experienced personnel who must remain updated on all current techniques (Wright 1994).

Modeling Tools

Modeling tools are ones that implement and measure constructability. This section includes both process-based and computer-based modeling tools. The ten modeling tools described as follows are included in about one third of the tool citations in the Constructability Committee of ASCE's Construction Institute's comprehensive on-line catalog. This indicates their significant importance in the constructability planning process. As in the policy/process-based tools, many of these modeling tools may appear obvious as good project management practices and easy to implement. However these tools bear reviewing from a constructability planning perspective.

Post-Construction Review Checklist. This is a tool to document and record the actual performance of a project once it is completed. All of the responsible participants shall meet together and discuss all phases of the project and any problems which occurred to give credit to positive aspects, and documentation for future improvement. At these post construction reviews, end of contract write-ups and as-built update suggestions should be made on corrective actions for future projects. All of the comments, good and bad, must be captured. All as-builts should be updated at this time and discussed as to their impact to the project. This is usually the last opportunity for lessons learned to be documented, hopefully so as not to be repeated. The resulting information from such a review should then be organized in some manner as to be retrievable and inspected at a later date. This use of end of contract reviews and write-ups should be at the beginning of any constructability program for latter projects (O'Connor et al. 1986).

Project Constructability Agreement. A drafted agreement for the project constructability team should state a commitment to constructability and the objectives set for the project. Other elements of the agreement may address additional objectives of the team, issues regarding communication, problem solving strategies, and responsibilities of individuals on the team (Russell and Swiggum 1994a).

Agency Constructability Checklists. A checklist is a tool which is developed to be used simply as a guide to remind one of all the procedures which have been developed to improve constructability. Checklists give an organization memory. A checklist will insure that proper procedures are followed and that now steps have been overlooked. This checklist can be general, on order for all phases of a project to follow, or the checklist can be specific to each task (Wright 1994).

Formal Implementation Process. A formal process is one in which steps and procedures are clearly defined. A constructability process can be implemented with varying states of formality (Gugel and Russell 1994; Russell et al. 1994). Most organizations have some level of informal constructability programs in place. If the process is formalized there is an assurance that issues will be addressed in a systematic manner. One manner to formalize an organization's planning and design process is to conduct constructability reviews which can be scheduled to take place at predetermined milestones within the planning, design and construction process. Figure 3 is a process model containing constructability functions for a transportation project (Fisher et al. 2000). It includes steps in the process for the planning phase (A1), the design phase (A2), and the construction phase (A3). These are further subdivided into twenty-one steps at the lowest level (A111 through A333).

Constructability Champion. A project champion is an individual who has the authority and responsibility for the implementation and adherence of the constructability program. Whereas the constructability engineer is used to understand and communicate constructability (policy/process-based tool), the champion has the authority to implement constructability (modeling tool). Each individual project should have such a champion. This individual must be high within the organization and must have the support of all of management. The champion must be connected with the project throughout all phases from planning through construction. It is the champion's responsibility to bring constructability issues to the attention of the organization and document lesson learned. For a constructability program to have an impact, resources need to be made available to the champion. These policies and documentation activities will require money up front in order to be implemented. There must be continuous support by management for any constructability program to work (ASCE 1991).

Value Engineering Process. Value engineering (VE) is a process by which a project is analyzed by function. The value of each function is compared to its total cost to implement. A VE study is a methodology used to measure these values and costs. The first task in a VE study is to develop possible approaches to achieving the owner's performance requirement by brainstorming. The objective of this analysis is to determine the most basic approach to fulfill the required functions. Once this base is determined, all improvements are analyzed on the basis of the additional cost over the base compared with the value of the improvement. The costs are easily determined and the value must be measured by the owner as to their perceived benefit. The use of VE should be used during the initial stages of development, but a VE analysis can also be performed by the contractor and owner prior to construction. During these studies, constructability issues will emerge and alternate methods will be introduced. The use of this cost/benefit criteria is to be used to find the best solution/approach towards the construction project (Dell'Isola 1997).

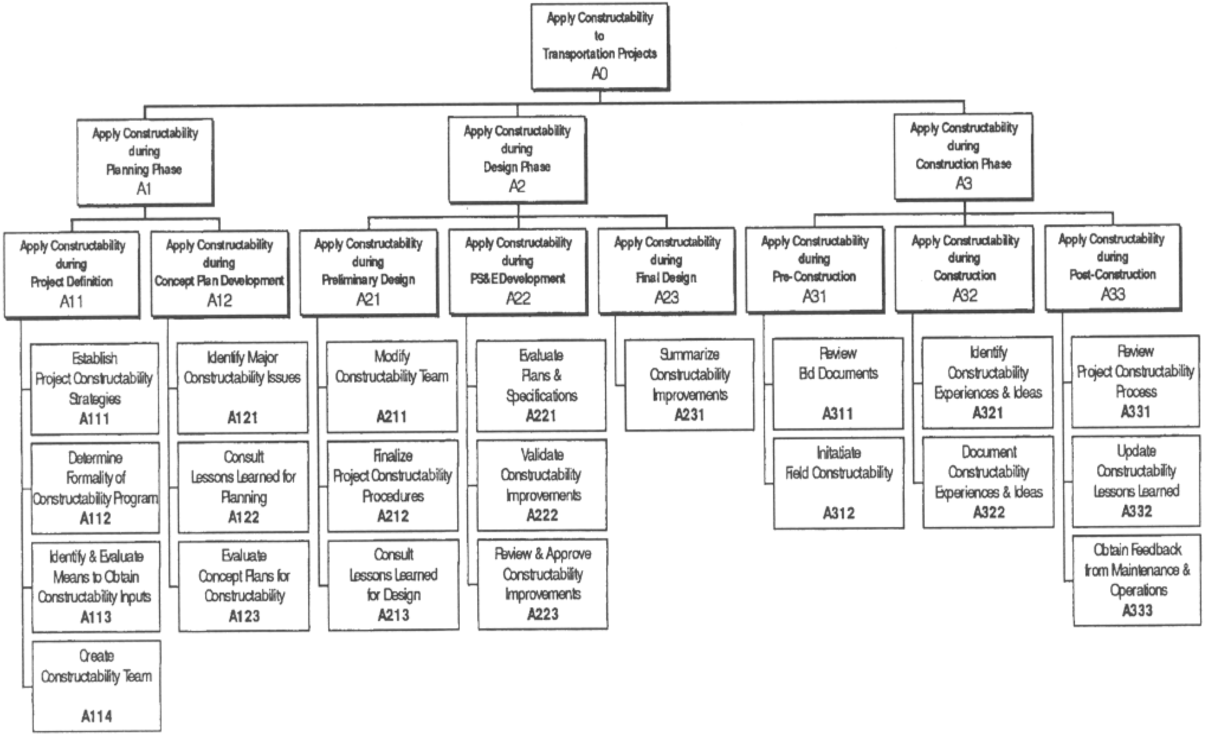

Figure 3: Constructability planning process framework (Fisher et al. 2000, ASCE)

Idea/Lessons Learned Log. An idea log is a way to capture all possible solutions or comments on improvements to design. Such a log is used in conjunction with some form of solicitation for suggestions. Figure 4 gives an example form for an idea log. An idea log can have the same format as a checklist and can even be the same form. These are a normalization of a common practice which is currently done repeatedly within each individual's mind. The use of idea logs gives the organization a learning capacity (CII 1993).

Issue Code	Lessons Learned	Phase	Function	B/C	Approval		
					Project	Database	Checklist
					☐	☐	☐
					☐	☐	☐
					☐	☐	☐

Figure 4: Example of idea/lessons learned log (Anderson and Fisher 1996)
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Critical Path Method. The critical path method (CPM) is a planning, scheduling and controlling tool. This method is based upon a network of all activities required to complete a project which are sequentially interconnected. Each activity within the network includes information regarding the function and the duration of the activity (Barrie and Paulson 1992). The use of CPM has become commonplace on most construction projects for the control of their schedule. However, the inclusion of the formal constructability review process steps (appearing in Figure 3) into the CPM is an important step towards formalization of the constructability review process.

Cost/Benefit Analysis Form. It is important that a user of constructability analysis understands the distinction between constructability reviews and VE, another cost/benefit technique presented earlier. VE focuses on functions/performance whereas constructability reviews focus on how well the construction documents convey design to facilitate construction, in other words, delivery. The analysis of cost/benefit for the implementation of constructability ideas is essential in order to sell the ideas in the first place. These concepts appear throughout the constructability literature (Russell et al. 1994; Dunston et al. 2001). Figure 5 illustrates a format for cost/benefit analysis (Anderson and Fisher 1996).

Constructability Suggestion Benefit/Cost Form

Project Name: ______________________________
Existing Design Description: ______________________________
____
Alternate Design Description: ______________________________
____

Assessment of Cost Impact

Redesign Cost:		Original Cost:	
Labor	______	Labor	______
Material	______	Material	______
•		•	
•		•	
Total	______	Total	______

Assessment of Benefit Impact to Project:
Cost Savings:

Actual (Hard$)		Perceived (Soft$)	
Labor	______	Schedule	______
Material	______	User Savings	______
•		•	
•		•	
		Total Benefit	______

Figure 5. Example of constructability benefit/cost analysis form (Anderson and Fisher 1996). Reprinted by permission of the Transportation Research Board of the National Academies

Constructability Resources. An outside source is any organization or person which is brought into a project who brings to the project a quality it was missing, such as when the owner or designer lack construction experience. An outside source of this knowledge is brought in which improves the constructability of the project prior to bidding. These sources of construction knowledge can come in the form of a construction management service, retirees or other agencies, or possibly panels of contractors. The use of an outside source allows the owner to capture insight on constructability issues which is not possible from its own staff. This approach is very useful when by law the contractual relationship prohibits contractors' involvement in the early stages of process (i.e., competitive bid process for many government agencies) (Nunally 1993).

Technology-Based Tools

Technology-based tools are tools which rely upon physical instruments, primarily advanced, cutting edge computer tools. Impressive progress in project modeling and computer-integrated construction has vastly improved constructability problems. The following groups of technology-based tools are contained in the majority (two-thirds) of the tool citations in the Constructability Committee of ASCE's Construction Institute's comprehensive online catalog. This indicates a trend in the strong reliance of computer technology. Computer technology can be divided into the following four groups, contained within graphical and non-graphical applications.

Graphical Computer-Based Tools. This group of tools can be divided into two categories – Computer Aided Design (CAD) and Other Graphical Applications (GA). The CAD group includes three and four D CAD and animation. The other GA group includes other graphical application tools, such as geographical information systems (GIS), hypermedia/multi-media, virtual reality (VR), and the World Wide Web.

1. *Computer Aided Design*: CAD uses a computer to perform the tasks of a conventional drafter. These tasks are performed with the aid of readily available CAD software packages. The use of CAD has revolutionized the drafting process, allowing for immediate updating of graphical data and the ability to overlay segments of the whole. Having the ability to graphically describe all aspects of a project reference frame eliminates conflicting drawings and allows for concurrent design at remote locations. Animation further allows the dynamics of a process to be demonstrated within a computer to find incompatible operations or to simulate construction operations/sequencing. These tools allow for many alternatives to be studied without the expense of constructing physical models, therefore maximizing the design for a minimum cost (Cherneff et al. 1991). The most recent three and four-D CAD applications to constructability, along with other visualization technologies will be discussed in detail in papers that follow in this section to this special publication.
2. *Other Graphical Applications – multimedia, VR, hypermedia/www:* GIS uses spatial data of physical features which are entered into the computer. Once entered, this digitized information can be manipulated and analyzed. GIS digitize maps and map-like information, including CAD drawings. It then integrates this data within other database information in order for a particular solution or application to be developed, providing multiple applications with the same frame of reference. With the recent advances in CAD products, many specialized graphical imaging systems have become available. These systems have the ability to import CAD and graphics files created elsewhere and perform a variety of specialized tasks to this data and then incorporate these improved designs to the original drawings. This technology allows many "what if" scenarios to take place without any physical changes to the physical world. This reduces the risk of constructability problems occurring later during field operations. GIS has been successfully applied to constructability in three-dimensional databases (Oloufa et al. 1992).

   Acquiring "constructability knowledge" requires substantial amounts of time, effort, and experience on the part of the project team. Unfortunately, most design engineers do not have the experience or the opportunity to make sufficient field trips to acquire this construction knowledge. Various forms of *multimedia* can enhance the learning process by improving the design engineer's long term retention of construction lessons learned. Multimedia pertains to the combined use of pictures, words, and sounds to relay information and the user the answers to questions asked. A multimedia constructability prototype was developed for the Indiana Department of Transportation at Purdue University (McCullouch and Patty 1993).

VR is any model or representation of physical experiences which are conveyed through a different media. This model can be expressed through more than one media at a time (i.e., sight, sounds and even touch). With the aid of computer technology we have the ability to model the real world and replay these sensations, allowing individuals to experience the physical world through artificial stimuli. VR allows individuals to perform tasks without actual physical changes to occur in the model. This allows physical activities to be optimized before any physical alterations are performed. Through the use of VR devices, organizations can optimize designs for ease of construction. VR devices can be as simple as a two dimensional program on a screen, similar to a video game, or as advanced as a holographic three dimensional image with mechanical devices attached to the body which place pressure that simulate the physical sensations associated with the image. VR has been used for constructability analysis, specifically for design review, albeit using the basic two dimensional on-screen program (Fu and East 1998).

Hypermedia/WWW is the use of a computer to sort through compiled data for associated key words and phrases. They user types or clicks on a word or phrase for which they wish to obtain information and the computer sorts through the entire database filters out data, and returns only the information relating to the key words entered. This is done today on the World Wide Web with search engines. One such intelligent web-based constructability system has been developed by the Corps of Engineers, entitled BCOE Advisor System (East et al. 2005). The web not only enhances constructability knowledge searches, but also collaboration of the web-based constructability team.

Non-Graphical Computer-Based Tools. This group of tools can be divided into two categories, just as the graphical tools were divided. The two categories for non-graphical computer-based tools include: (1) databases, and (2) analytical tools, such as those used in simulation and artificial intelligence.

1. *Databases*: A database is a collection of various pieces of information which have been organized into related areas and structured in a manner so as to provide easy access and quick retrieval. Such databases of constructability lessons learned have been used for quite some time (Russell and Swiggum 1994b). More recently, classification schemes for database organization of constructability information have been attempted

(Hanlon and Sanvido 1995). Figure 6 illustrates a centralized constructability database, and the various sources for such knowledge.

One architecture for storage of data is by object orientation, where data is stored by object within a hierarchical structure based upon natural relationships between these objects. Contained within each object is its structure regarding its relationships, nature and behavior, in terms of methods and procedures. This object oriented structure allows the user to retrieve any level of detail of the area of interest. A user can retrieve all of the objects which are components of a particular system or retrieve the information regarding one specific object. Object orientation can be very useful when there are many users distributed throughout an organization. Object orientation allows for easier monitoring or tracking of singular objects or object types which are related or used for more than one separate operation or task within a process (McCullouch and Patty 1993). Constructability analysis can be facilitated by asset information management that comes from bar coding technology and radio frequency equipment tagging. Information from these technologies can be integrated into the constructability database for enhanced analysis.

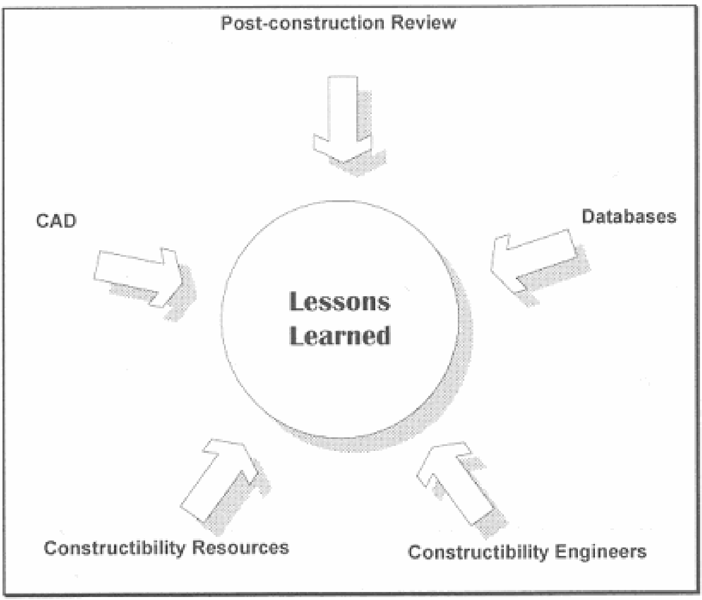

Figure 6. Sources of lessons learned (Anderson and Fisher 1996)
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2. *Analytical – simulation, artificial intelligence, decision support systems, expert systems*: Analytical tools include computerized work process simulation models, decision support systems (DSS) and intelligent decision support systems (IDSS). DSS includes expert systems (ES) where a knowledge base might be used to aid decision making.

   An ES is a structured program which provides the user with solutions to problems by requesting information that will allow it to apply rules and select possible outcomes. It is constructed around criterion defined by a human expert. An ES is based upon a decision tree designed by an expert within a specific domain. The system is designed to ask the user a set of questions which leads to a solution to the problem. An ES can be based upon a certainty system such that depending upon the answers to the questions the solution is assigned a certainty factor. An ES provides a permanent collection of solutions for particular symptoms and can infuse the knowledge of many experts. Currently there are many ES software packages which can be used as a shell for any particular usage. The ES can include simple Boolean logic or even neural networks (discussed in the next paragraph). An ES should be used as a tool to assist in the planning, design and construction phase by providing advice to augment the knowledge base of your organizations experts. ES programs that have been applied to constructability analysis include drilled shaft foundations (Fisher et al. 1995), roof designs (Fu et al. 1997), and rebar constructability diagnosis (Navon 2000).

   IDSS includes neural networks for machine learning. This technology employs pattern recognition to make decisions based upon partial, incomplete or inexact information. Neural networks (NN) are based upon the biological structure of the human brain. These logic structures are design to simulate the activities of neurons within the human brain. NN's solve problems through the use of pattern recognition and various algorithmic techniques. These networks allow complex problems to be solved using human mimicking learning and application (heuristic) processes which are performed by computers. The use of NN's has been applied to constructability analysis for modularization (Fisher and Rajan 1996) and reinforced concrete beams (Skibniewski 1997).

Tool Integration

As previously discussed in the section on "formal processes," Figure 3 contains twenty-one steps for a generic constructability project program. Each of the twenty-seven tools that are presented in this paper has an area of application or more likely more than one area of application to the complete constructability planning process (CPP). Figure 7 illustrates these twenty-seven tools aligned with each step in the process (Fisher et al. 2000). These links between process steps and tools provides the user with a framework. This framework enables a user to easily map and implement a constructability planning process on their project.

Name of Tool	Constructability Functions																				
	A111	A112	A113	A114	A121	A122	A123	A211	A212	A213	A221	A222	A223	A231	A311	A312	A321	A322	A331	A332	A333
Policy and objective statement	x				x				x												
Constructability Meeting				x			x		x		x					x					
Operation and maintenance input							x														x
Constructability organization structure									x							x					x
Suggestion Forum							x				x					x					
Pre-Bid Conference															x						
Pre-Construction Conference																x					
Contract Clauses/Incentives															x						
Partnering								x								x					
Contractor-Determined Schedule																x					
Implementing Responsibility Matrix				x					x							x					x
Team Building				x				x													
Constructability Engineers			x			x		x		x						x					
Post-Construction Reviews						x				x									x		
Project Constructability Agreement				x					x							x					
Agency Constructability checklists											x									x	x
Formal Processes		x							x												
Constructability Champion				x																	
Value Engineering								x								x					
Idea/Lesson Learned Log							x					x						x	x		x
Critical Path Method							x				x										
Cost/Benefit Analysis							x					x				x					
Constructability Resources			x			x		x		x						x					
CAD							x				x										
Hypermedia/Multimedia/CD ROM/Hypertext						x				x	x							x			
Databases						x				x										x	x
Art. Intelligence, Decision Supt., Expert Syst.																					

Figure 7. Tool/function roadmap (Fisher et al. 2000, ASCE)

Conclusions

This paper presents the latest research on twenty-seven tools used for the implementation of constructability on projects. The first group of tools includes thirteen policy/process-based ones that are the most basic and easiest to implement on a project. The second group of tools includes ten modeling tools that are for slightly more advanced project constructability planning. Thirdly, four high technology tool groups are discussed, along with the numerous citations on the application of these tools to constructability today. Finally, a CRP framework is provided that links these twenty-seven tools to constructability project functions, thus enabling a user to facilitate the application of constructability on any given project.

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CA4PRS: A Constructability Analysis Tool for Urban Highway Rehabilitation Projects

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Abstract

A large portion of pavement in the California highway system, which was mostly built between 1955 and 1970, has now exceeded their 20-year design lives and are seriously deteriorated. Since 1998, the California Department of Transportation (Caltrans) has launched Long-Life Pavement Rehabilitation Strategies (LLPRS) to rebuild approximately 2,800 lane-km of urban freeway over 10 years. This paper introduces a constructability analysis software program, called CA4PRS (Construction Analysis for Pavement Rehabilitation Strategies), intended for use as a planning and decision making tool for LLPRS projects. CA4PRS can be used to optimize construction and traffic management plans for highway rehabilitation projects by integrating scheduling interfaces, pavement design and materials selection, lane closure tactics, and contractor logistics and resources. It was designed to help agencies and paving contractors develop construction schedules that minimize traffic delay and agency costs in their decision-making process. Application to several urban freeway rehabilitation projects with heavy traffic volume, including I-10 Pomona, I-710 Long Beach, and I-15 Devore projects in California has demonstrated the tool's value.

Introduction

Need for Highway Rehabilitation in California. Most state highways in the United States, built during the 1960s and1970s, have exceeded their twenty-year design lives and suffer pavement deterioration due to continuously increasing traffic demand and heavier vehicles. This degradation adversely affects road user safety, ride quality, vehicle operation, and highway maintenance costs, and it causes delays. The

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deteriorating condition of pavement has led state and federal transportation agencies have turned their attention from new highway construction to 4-R projects: Restoration, Resurfacing, Rehabilitation, and Reconstruction (Herbsman and Glagola 1998).

The California Department of Transportation (Caltrans) launched the Long-Life Pavement Rehabilitation Strategies (LLPRS) program in 1998 to rebuild approximately 2,800 lane-km (1,740 lane-miles) of deteriorated freeways among the 78,000 lane-km (48,648 lane-miles) of the state highways. It selected the LLPRS candidate projects based on their poor pavement condition and ride quality, and on whether they had a minimum 150,000 Average Daily Traffic (ADT) or 15,000 Average Daily Truck Traffic (Caltrans 1998). Most of the candidate projects were Portland cement concrete (PCC) freeways in the Los Angels Basin and the San Francisco Bay Area, were twenty-five to forty-five years old, and had not yet had any major rehabilitation or reconstruction.

Traditionally, urban freeway rehabilitation or reconstruction projects in California have used 7- or 10-hour nighttime closures because daytime closures cause unacceptable delays to weekday peak travel. However, nighttime closures may result in longer total closure times, higher construction and traffic-handling costs, longer construction periods, and greater traffic delay to road users (TRB 1998). In recognition of these drawbacks, Caltrans has adopted an innovative highway rehabilitation strategy of accelerated construction with continuous (round-the-clock) operations during 55-hour weekend or 72-hour weekday closures for LLPRS projects.

CA4PRS: A Decision-making Support Tool. The need for a sophisticated production estimate model integrating construction and traffic operations for highway rehabilitation projects is the motivation for developing *CA4PRS* (Construction Analysis for Pavement Rehabilitation Strategies) software, the subject of this paper. The Institute of Transportation Studies at the University of California at Berkeley developed the *CA4PRS* model with support from the State Pavement Technology Consortium (California, Florida, Minnesota, Texas, and Washington), a FHWA pooled-fund program (Lee and Ibbs 2005).

CA4PRS is a planning tool designed for use during the planning, design, and construction stages of rapid (accelerated) highway rehabilitation projects. The model estimates the optimized distance of highway pavement rehabilitation or reconstruction (lane-km and centerline-km) that can be completed during various types of closures by taking into account project constraints of design, construction, and traffic operations. As a knowledge-based computer model using Monte Carlo simulation, *CA4PRS* evaluates various alternatives for highway pavement rehabilitation from the perspective of schedule and production. The main rehabilitation parameters compared are: pavement rehabilitation type alternatives, scheduled interfaces between major activities, contractor resource constraints, pavement design and material properties, and lane closure tactics.

CA4PRS can be integrated with macro- and microscopic traffic simulation models to quantify road user cost (RUC) caused by highway rehabilitation activities. When combined with such traffic models, the *CA4PRS* software can help determine which pavement structures and rehabilitation strategies maximize on-schedule construction without creating unacceptable traffic delays. This information is vital in balancing the three competing goals longer-lived pavement, faster construction, and decreased traffic delay during closures.

Modeled Rehabilitation Strategies

Three widely-accepted highway rehabilitation strategies incorporated in *CA4PRS* as individual analysis modules are: (1) the Portland cement concrete (PCC) reconstruction strategy, where the old pavement is rebuilt with a PCC slab and optional pavement base structure; (2) the crack-seat and asphalt concrete overlay (CSOL) rehabilitation strategy, where the old pavement is optionally cracked/seated and overlaid with new asphalt concrete (AC) layers; and (3) the full-depth AC (FDAC) replacement strategy, where the old pavement is replaced with full-depth AC layers.

PCC Reconstruction Module. As illustrated in Figure 1, three alternative new pavement cross-sections, i.e., 203 millimeters (8 inches), 254 millimeters (10 inches), and 305 millimeters (12 inches) are available in the built-in menu for the PCC reconstruction strategy. The user can create his/her own cross-section profile if the default cross sections in the built-in menu are not applicable to the project, including any additional demolition depth that might be necessary to comply with the new FHWA height clearance requirements for bridge underpasses or overpasses.

There are three default cement materials to choose from: 4-, 8-, and 12-hour curing time mixes to achieve a minimum traffic opening strength [e.g., 2.8 MPa (400 psi) of flexural strength with the 3-point beam test in California]. Use of different concrete curing times will allow for extra construction time that could not be attained when using ordinary PCC. In addition to the available curing time in the menu, a user can also define concrete curing time.

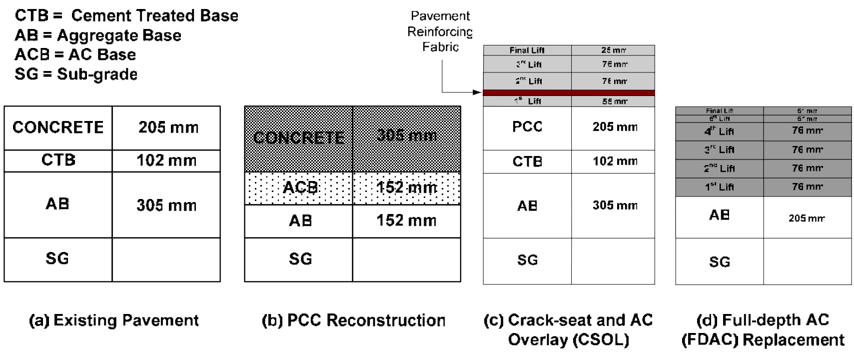

Figure 1. Typical pavement cross-section changes modeled in *CA4PRS*

CSOL Rehabilitation Module. The CSOL rehabilitation strategy usually involves placing three to four new AC layers, 200 millimeters (8 inches) to 250 millimeter (10 inches) — as is typical in LLPRS designs — in most cases on top of the cracked and seated old PCC pavement (Figure 1). The user is able to create a project-specific pavement cross-section by specifying the number of AC layers required and the layer thickness.

The CSOL analysis module permits full- and half-lane closure tactics. With CSOL full-closure, one direction of the freeway is completely closed for rehabilitation and traffic is switched to the other side of the freeway with counter-flow traffic using median crossovers. The main lanes and shoulders are completely overlaid, layer by layer and lane by lane, on the side of the roadbed that is closed. Usually, the paving operation alternates the sequence of paving lanes to minimize waiting time.

FDAC Replacement Module. The FDAC replacement strategy requires complete removal of the old pavement and partial trimming of the aggregate base to accommodate the specified depth of the new AC pavement. In LLPRS projects, a rich bottom AC layer will likely be placed on top of the recompacted aggregate base, followed by four or five AC layers paved sequentially, with a total thickness ranging from 305 millimeters (12 inches) to 381 millimeters (15 inches) (Figure 1).

The FDAC analysis module includes two lane closure tactics: single- and double-lane rehabilitation. A major benefit of double-lane rehabilitation is the interlocking of multiple AC layers by overlapping longitudinal joints between adjacent lanes. The single- and double-lane rehabilitation concept for the FDAC replacement is similar to the PCC reconstruction methodology except that FDAC replacement does not require paving both lanes in one pull.

Cooling Time Interaction with MultiCool. *MultiCool,* a numerical AC cooling simulation program that calculates cooling time for multi-layer paving, is embedded in *CA4PRS* to check the suspension of the paving operation arising from the cooling time for the CSOL rehabilitation and FDAC replacement strategies (Timm et al. 2001). The *CA4PRS* menu provides the option of user-specified or *MultiCool*-calculated AC cooling times. These cooling times are the time required prior to the placement of next lift or opening to traffic. In the first option, the user specifies the cooling time for each of the lifts as part of the cross-section definition and *CA4PRS* optimizes the sequence of lift placement to minimize suspension time needed for cooling. In the second option, *CA4PRS* calls on *MultiCool* to calculate cooling time for each lift of AC for each lane during each simulation. The environmental conditions are input for up to four different periods per day, and *CA4PRS* interpolates numerical variables for the time of day of AC lift placement during simulation.

System Interfaces

Computational Background. *CA4PRS* provides dual analytical approaches in dealing with the input variables: deterministic or probabilistic modes. In the deterministic analysis approach, the input parameters including resource and scheduling constraints (activity lead-lag time relationships) are treated as constants without any variations. The deterministic analysis is faster and has fewer input data requirements than the probabilistic analysis. In the probabilistic (stochastic analysis) approach, the input parameters are treated as random variables to generate the likelihood of achieving different pavement rehabilitation production rates, utilizing Monte Carlo simulation. Uniform, normal, log normal, beta, geometric, triangular, truncated normal, and truncated log normal probabilistic distributions are available to specify the appropriate parameters for distribution of each variable selected.

The *CA4PRS* software runs on Microsoft *Windows 95/NT4.098/2000/XP*™ or higher operating systems. It is developed in Microsoft *Visual Basic 6.0* and utilizes a Microsoft *Access 2000* database for data storage, although it does not require Microsoft *Access* to be installed to run the software. The database interface helps recall input parameters from previous analyses and transmit project information to other users. *CA4PRS* utilizes a number of royalty-free third-party tools to enhance the user friendliness, the versatility of the user interface, and the presentation quality of the program. *CA4PRS* employs a multiple-document interface, similar to Microsoft *Excel*™ or Microsoft *Word*™*,* which enables multiple projects and analyses to be opened, viewed, and compared simultaneously. As illustrated in Figure 2, *CA4PRS* employs a systematic menu structure that groups menu items in an intuitive manner.

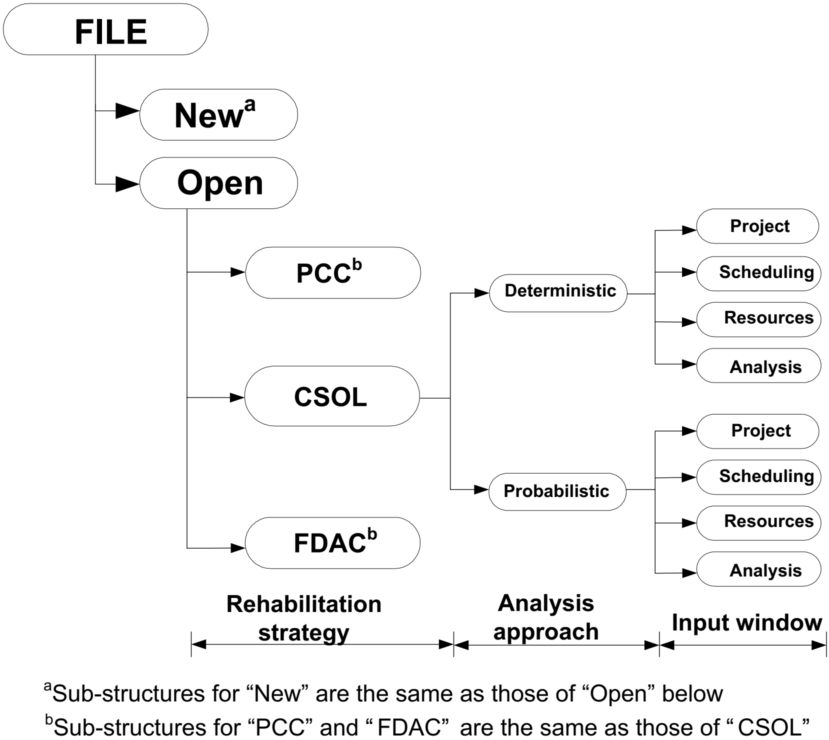

Figure 2. *CA4PRS* menu tree and analysis hierarchy

Input Interfaces. A single computer can run *CA4PRS* as a stand-alone application or it can run on a network server to allow multi-user access and database sharing. *CA4PRS* starts with a prompt for user input with the following four tab windows:

- *Project Details*: The user enters basic project information, including an analysis identifier, project descriptions, route name, post (station) miles, location, etc. The user enters total lane-kilometers (or lane-miles) to be rehabilitated, which acts as the baseline for computing the total number of closures required. *CA4PRS* then computes this total based on predicted production rates.
- *Scheduling*: Users enter minimum times required for mobilization and demobilization activities, such as site preparation, clean up, and most importantly, deployment and removal of traffic control (Figure 3). The user specifies lead-lag relationships and minimum-time interfaces among major operations. Three alternative closure time frames are available: nighttime, weekend, and continuous closures.
- *Resource Profile*: The user specifies contractor logistics and resource

constraints (Figure 4). Resource inputs such as number of demolition hauling trucks per hour rely on the user's knowledge, experience, and personal judgment for accuracy.

- *Analysis*: The user can select from the multiple input categories: construction windows; rehabilitation sequence with respect to lane closure tactics; mix design in terms of concrete curing and AC cooling time; pavement cross-section changes; and truck-lane width (Figure 5).

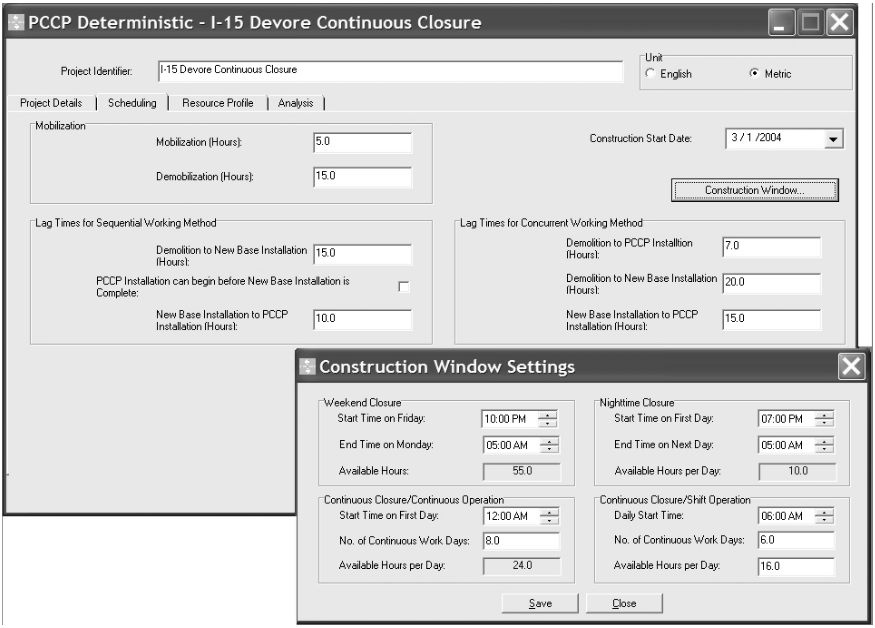

Figure 3. Input screenshot of the scheduling input for *CA4PRS* concrete deterministic analysis

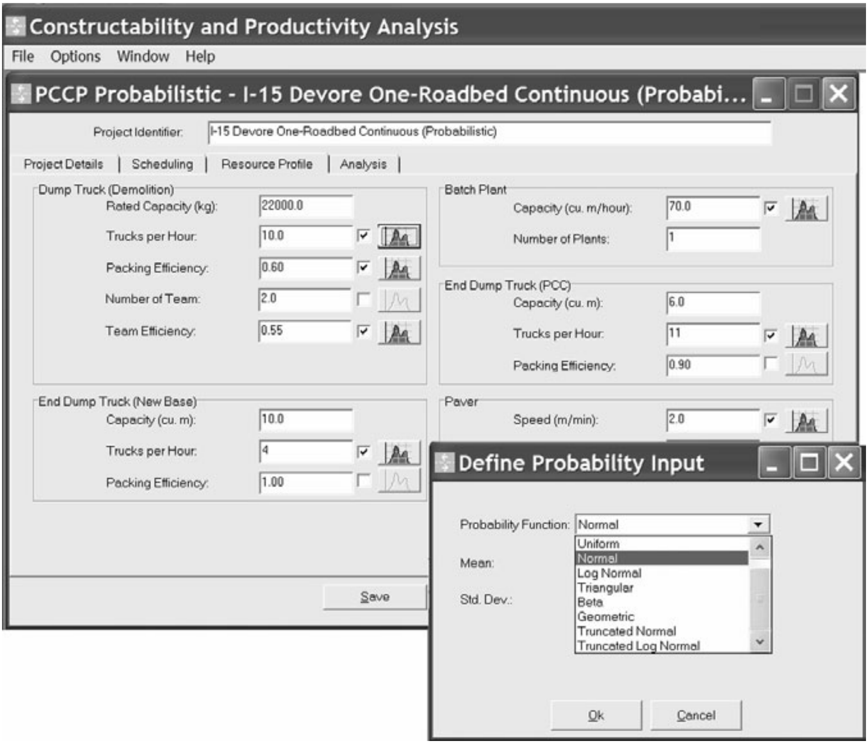

Figure 4. Input screenshot of the resource profile input for *CA4PRS* concrete probabilistic analysis

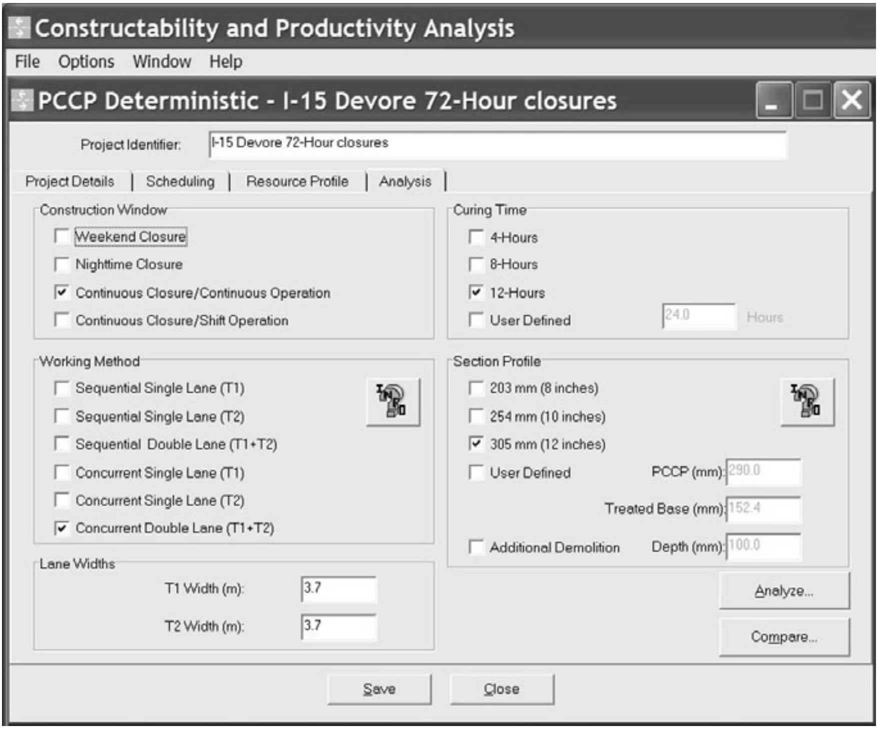

Figure 5. Input screenshot of the analysis input for *CA4PRS* concrete deterministic analysis

Outputs and Reports

CA4PRS employs a multiple-document interface, enabling multiple projects and analyses to be viewed simultaneously. *CA4PRS* provides extensive graphical and tabular outputs, and incorporates a report feature that allows input and output information to be printed in PDF or RTF format. In deterministic mode the output comes in two parts: *Production Details* and *Production Chart* (see Figure 6). *Production Details* includes a user input summary and the principal analysis results; that is, the maximum production of each rehabilitation scenario and the number of closures required to finish the project. *Production Chart* shows a line-of-balance schedule illustrating the linear progress of the main rehabilitation operations over time. The user can also generate a comparison table, summarizing the main inputs and outputs relative to combinations of various production variables; e.g., construction window, section profile, rehabilitation sequence, etc.

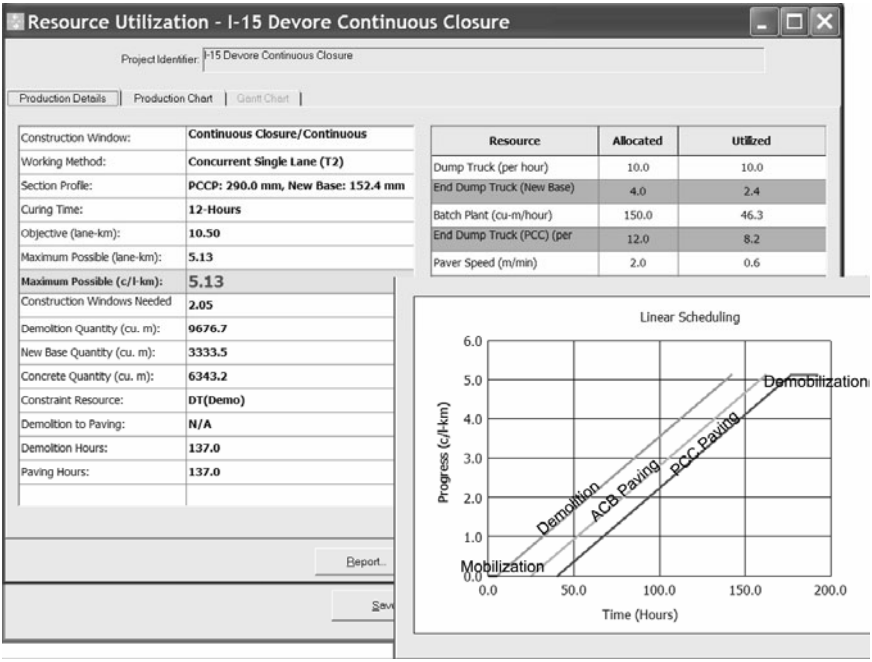

Figure 6. Output screenshot of *Production Details* for *CA4PRS* concrete deterministic analysis

The probabilistic approach output windows are similar to the ones with the deterministic approach except for a distribution plot of maximum production range generated with a Monte Carlo simulation (Figure 7). Though the probabilistic approach requires more user inputs, it provides a more realistic production estimate. In viewing a Sensitivity Chart, it also permits the user to see the relative contribution of the input variables to production as a whole.

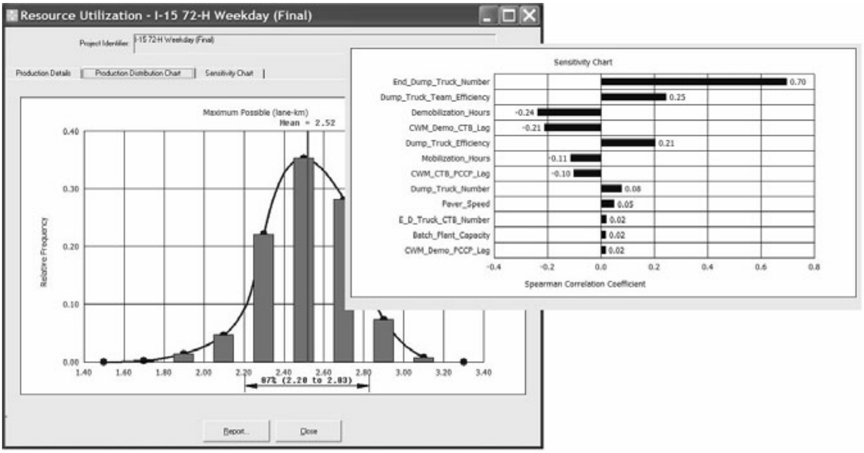

Figure 7. Output screenshot of Production Distribution and Sensitivity charts for *CA4PRS* concrete probabilistic analysis

Validation and Deployment

The *CA4PRS*-sponsoring states now have a unique opportunity to validate and further calibrate their processes and tools using the software for urban highway rehabilitation projects with high traffic volume and accelerated construction.

Validation Projects. The *CA4PRS* model has been applied to urban freeway rehabilitation projects, including the Interstate-10 Pomona, Interstate-710 Long Beach, and Interstate-15 Devore projects. The first *CA4PRS* validation project was the LLPRS Concrete Pilot Project on I-10 in Pomona. Here, 2.8 lane-km (1.67 lane-mile) of deteriorated truck-lane was rebuilt during one 55-hour weekend closure (Friday, 10:00 p.m. to Monday, 5:00 a.m.) (Lee et al. 2002). The *CA4PRS* analysis precisely predicted the contractor's actual production rate.

Next, *CA4PRS* was used to evaluate the LLPRS Asphalt Pilot Project on I-710 in Long Beach, where 26 lane-km (15 lane-mile) of deteriorating PCC pavement was replaced with long-life asphalt concrete pavement in eight 55-hour weekend closures (Lee et al. 2005a). *CA4PRS* analysis warned that the contractor's initial staging-plan of rehabilitating two FDAC sections (about 0.8 km) together with one CSOL section (1.3 km) per weekend was overly optimistic. The contractor revised his production plan based on the production levels estimated by *CA4PRS*. Actual production performance was within 5% of those estimates.

CA4PRS was also used by Washington State DOT engineers to explore rapid rehabilitation strategies on two projects: Interstate 5 (I-5) in Federal Way (Seattle), where a 5-km section will be replaced with PCC over asphalt base; and the reconstruction of a portion of southbound I-5 beneath the Convention Center in

Seattle. This section is one of the highest volume locations in Washington State, and work on it was successfully completed in 2005 using a scheme of four weekend closures.

In 2004, the Minnesota Department of Transportation (MNDOT) implemented *CA4PRS* on two resurfacing projects. Both jobs involved milling and bituminous paving: one was a nighttime operation on Interstate 494, and the other was a combination of night- and complete-weekend closures on Interstate 393.

Deployment Project. Recently the *CA4PRS* tool was used with traffic simulation models to select the most economical rehabilitation scenario for the I-15 Devore project. The 4.5-km (2.7 lane-mile) reconstruction project, which would have taken ten months using traditional nighttime closures, was completed over two nine-day periods using one-roadbed full closures with counter-flow traffic and around-the-clock (24/7) construction operations in late 2004 (Lee et al. 2005b). The preconstruction analysis with *CA4PRS* concluded that the one-roadbed continuous closures were the most economical scenario when compared to 10-hour traditional nighttime or 55-hour weekend closures from the perspective of schedule, delay, and cost (see Table 1). Compared to traditional 10-hour nighttime closures, the preconstruction analysis indicated that the extended closure scenario had about 80% less total closure time, about 30% less road user cost due to traffic delay, and about 25% less agency cost for construction and traffic control.

Table 1. *CA4PRS* estimates of schedule, traffic, and cost for the I-15 Devore closure alternatives

Closure scenario	**Schedule comparison**		**Traffic delay**		**Cost comparison**	
	Closure number	Closure hours	Road user cost ($M)	Max delay (minute)	Agency cost ($M)	Total cost[1] ($M)
72-hour weekday	8	512	6.6	75	12.6	19.2
55-hour weekend	10	550	12.7	196	15.1	27.8
One-roadbed continuous	2	400	6.1	196	9.9	16.0
10-hour nighttime	220	2,200	10	36	20.4	30.4

[1] Total cost = Road user cost + Agency cost

More detailed constructability analysis, from the production and scheduling point of view, was performed using the *CA4PRS* model in the comparison of (1) concrete mix design, (2) pavement base type, and (3) outer truck-lane width. The *CA4PRS* scheduling analysis answered questions regarding how quickly the whole project could be completed for each permutation of the three variables by estimating the maximum production (in distance) per closure and the total number of closures required to complete the entire project.

Based on the constructability analysis results, Caltrans decided to use (1) the concrete mix of 12-hour (Type III cement) curing time rather than fast-setting hydraulic cement concrete, (2) asphalt concrete base rather than lean concrete base, and (3) a widened truck lane rather than normal truck lane tied with new concrete shoulder.

This "Rapid Rehab" approach saved 25% ($6 million) in agency costs and significantly reduced road user costs (by $2.5 million) as the maximum peak-hours delay was reduced from an estimated 90 minutes to 50 minutes during construction. According to web surveys, road users showed a dramatic change in their perception of the accelerated urban freeway reconstruction project utilizing state-of-practice innovations and technologies. The surveys showed a change in perception from initial reluctance and objection to support.

Potential Payoffs and Outreach. The *CA4PRS* model was developed to provide road agencies and the transportation industry with a systematic construction engineering and management tool in their decision-making process for the rehabilitation and reconstruction of highways. The model is especially beneficial for agencies dealing with high traffic volume in urban areas, particularly during the planning and design stages when the resulting analysis can be used to integrate pavement design, construction logistics, and traffic operations. The model is also useful for design and construction engineers, consultants, and paving contractors in providing cost savings by comparing alternatives during estimating and project control stages.

Various traffic lane closure strategies and pavement design alternatives can be evaluated with the goal of maximizing new pavement life expectancy and construction production, and minimizing traffic delay and agency costs. During the design and construction phases of highway rehabilitation projects, *CA4PRS* helps transportation agencies, contractors, and consultants: to develop construction staging plans, to establish Critical Path Method schedules, and to outline "cost (A) + schedule (B)" contracts that include specifications for incentives and disincentives.

CA4PRS has been presented at national conferences and workshops hosted by the Transportation Research Board (TRB), American Association of State Highway Transportation Officials (AASHTO), and the Federal Highway Administration (FHWA). The background of *CA4PRS* and its implementation experience have been described in transportation journal articles, *TR News,* and in industry newsletters, such as the ones published by the American Concrete Paving Association (ACPA) and the National Asphalt Pavement Association (NAPA). Hundreds of *CA4PRS* posters and brochures have been distributed to potential users, and information on the software is available on the Caltrans and U.C. Berkeley websites.

The Caltrans Division of Research and Innovation and its Partnered Pavement Research Program are completing a *CA4PRS* outreach and deployment program for pavement and traffic engineers, particularly in metropolitan districts. This outreach includes workshops in California and in the three other consortium states. The workshop is a two-day hands-on training, interactive software demonstration, and computer lab course exercises using real sample projects. Over the last three years, about 400 transportation engineers from the sponsoring DOTs have attended the intensive training seminars.

Conclusions and Future Development

A large portion of pavement in the California highway system, which was mostly built between 1955 and 1970, has now exceeded its twenty-year design life and has seriously deteriorated. In 1998, the California Department of Transportation (Caltrans) launched its Long-Life Pavement Rehabilitation Strategies (LLPRS) Program to rebuild approximately 2,800 lane-km of urban freeway over ten years. This paper introduces a constructability analysis software program called *CA4PRS* (Construction Analysis for Pavement Rehabilitation Strategies) that is intended for use as a planning and decision making tool. *CA4PRS* can be used to optimize construction and traffic management plans for highway rehabilitation projects by integrating scheduling interfaces, pavement design and materials selection, lane closure tactics, and contractor logistics and resources. The software was designed to help agencies and paving contractors develop construction schedules that minimize traffic delay and agency costs in their decision-making process. Application to several urban freeway rehabilitation projects with heavy traffic volume — including the I-10 Pomona, I-710 Long Beach, and I-15 Devore projects in California — has demonstrated the tool's value.

CA4PRS is being upgraded to improve user friendliness, to add more rehabilitation strategies, and to integrate it with traffic simulation models. Version 1.5 will be expanded to cover more rehabilitation features, such as the rehabilitation of continuously reinforced concrete pavement (CRCP) and dowel-bar retrofits. In the update for the *CA4PRS* Version 2.0, schedule analysis will be integrated with traffic simulation tools such as the Demand-Capacity Model — based on the Highway Capacity Manual — to calculate road user delay in the construction work zone, and to estimate agency construction and traffic handling costs (TRB 2000). Eventually the concept of the total cost (as the sum of agency and road user costs), based on the scheduling, traffic, and cost analyses, will be provided to select the most economical highway rehabilitation scenarios.

Acknowledgements

The research team would also like to acknowledge the information, feedback, and partial funding of *CA4PRS* field case studies contributed by the American Concrete Pavement Association and the National Asphalt Pavement Association. The research team also appreciates the implementation information provided by the Caltrans field engineers, especially the I-10 Pomona, I-710 Long Beach, and I-15 Devore project teams. The views expressed in this paper are solely those of the authors and do not represent those of any official organization.

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A Cost and Benefit Model for Constructability Review Implementation

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Abstract

While proponents of conducting constructability reviews are generally confident of quantitative and qualitative rewards of implementing this element as part of the project development process, an accepted model for evaluating the benefits versus costs is lacking. Anecdotal reports suggest the benefits are quite high compared to the costs, sometimes reflecting those of high profile projects, and previous research on the relationship has provided varied results. The assumptions regarding which benefits can clearly be attributed to constructability reviews have been suspect as well. Assistance with objectively evaluating the success and impacts of constructability reviews on projects is needed. This paper presents a study to develop a model for quantitatively comparing the benefits and costs associated with the formal implementation of constructability reviews in a state transportation agency (STA). Although the model as developed is specific to STAs, it may be generalized to fit other project types and contracting scenarios. The benefit/cost model developed is founded on the proposition that constructability reviews provide efficiencies that result in significant reductions in costs and schedule for planning, design, and construction. The researchers have developed worksheets designed to guide practitioners through application of the model, and present application of the worksheets to two projects from the Northwest region of the Washington State Department of Transportation (WSDOT), producing results which showed the benefits of conducting constructability reviews outweighed the costs. The fundamental features of the model are also recommended for assessing the success of constructability reviews for construction projects outside of the transportation field.

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Introduction

A common goal among project owners is to create quality facilities at a reasonable cost and in a timely manner. It is with this goal in mind that many owners place emphasis on the constructability of their projects. Constructability reflects the ease with which a project can be built and the quality of a project's contract documents. It is affected by the consideration of construction methods, capabilities, and resources in the project design, and by the attention paid to creating complete, clear, and error-free contract documents (McManus and Gambatese 1997). Constructability is a project property that all personnel involved in the planning, design, construction, operation, and maintenance of a facility can influence to create projects that are biddable, buildable, and maintainable.

The importance of constructability to project success has motivated many state transportation agencies (STAs) to develop constructability review processes (CRPs). Formal CRPs provide a framework within the STA's project development process (PDP) to ensure the incorporation of construction knowledge in project designs and the development of quality contract documents in a timely manner. CRPs can vary considerably between different STAs, especially with regards to both formality and level of implementation, but are commonly structured to include periodic project reviews during the planning and design phases. Guidance for STAs on establishing and implementing constructability review programs and procedures is available. *NCHRP Report 390*, "Constructibility Review Process for Transportation Facilities" (NCHRP 1997a), and *Report 391*, "Constructibility Review Process for Transportation Facilities—Workbook" (NCHRP 1997b), provide background on the topic and describe tools created to support the development and implementation of effective CRPs. Additional assistance is provided in the *Constructibility Review Best Practices Guide* authored by the American Association of State Transportation and Highway Officials (AASHTO) Highway Subcommittee on Construction (AASHTO 2000). This document concisely describes the key elements of a CRP and also examines the extent of CRP implementation in the state transportation agencies throughout the United States. The findings reveal a lack of widespread implementation of CRPs which the subcommittee attributes, at least in part, to a perception of the CRP as too resource intensive and to the lack of a procedure for assessing the costs and benefits of the CRP. As a critical means to encourage confidence in the efficacy of CRPs, the AASHTO *Best Practices Guide* cited the need for a model that provides a measurement of the success of a CRP. Such a model should incorporate the cost of and benefits received from CRP implementation on a regular basis.

In recognition of this need, the National Cooperative Highway Research Program (NCHRP) funded a study to: (1) develop techniques and procedures to quantify the costs and benefits of constructability reviews; (2) demonstrate the techniques and procedures through case studies; and (3) provide guidance on the application of the concepts of constructability reviews at various levels of expertise, degrees of effort, and points during the PDP. The study was intended to compliment previous studies by examining CRP implementation with the objective of addressing barriers to successful implementation and amplifying the flexibility of the CRP model to suit varied STA resource capabilities and project types. This paper describes the model which was developed, along with the application of the model to two transportation projects.

Previous Research and Recommended Practice

As noted previously, the commonly recommended CRP approach is to address constructability during each major phase of the project development process (NCHRP 1997a, 1997b; McManus et al. 1996). Outputs during the STA's standard PDP serve as inputs to scheduled constructibility reviews. A review, for example, is conducted when the schematic design documents are completed, corresponding approximately to the 30% point in overall design. The output of the constructibility reviews is then fed back into the PDP which continues in its normal fashion until the next scheduled CRP review milestone. *NCHRP 391* specifically provides detailed guidance on applying CRPs, including staffing, level or frequency of reviews, method for conducting reviews, and how tools may be used. In its *Constructability Concepts File* (CII 1987), the Construction Industry Institute provides "representative good practices in a manner that will enable practitioners in any organization to take advantage of the lessons learned by others and apply them in their organizations and on their project." This work, along with other research on the topic (for example: CII 1986; O'Connor et al. 1987; O'Connor and Miller 1994; and Uhlik and Lores 1998), focuses on the general area of constructability and how engineers and architects can manage and modify a design to facilitate construction, but these resources do not provide quantitative evidence as to its impact.

Prior assessment of the ratio of benefits to costs associated with constructability reviews has been minimal and the findings varied. *NCHRP Report 391* presents a benefit/cost analysis tool consisting of a pair of sample forms for documenting costs and benefits. The tool focuses exclusively upon the specific ideas that emerge from constructability reviews, ignoring ancillary benefits to the project associated with improved constructability. It also assumes redesign for each constructability idea and certainty of the outcome of design in the absence of a CRP, the former assumption not always being the case and the latter assumption not being widely accepted. The authors of this paper assert that a more encompassing model is needed to capture the true range of CRP costs and significant impacts.

Russell et al (1994) conducted a comparative analysis of three different approaches to addressing constructability that were implemented on four different construction projects: a commercial office building development, a consumer products manufacturing facility, and two petrochemical projects. While the documentation for making a benefit-cost comparison was not available on the commercial office building project, the implementation of constructability review processes on the other three projects was found to result in a benefit-cost ratio of 10:1 on each project. In this study, costs were calculated using two measures: constructability effort-hours as a percent of total construction field hours, and program cost as a percent of total project cost. Benefits were calculated based on an order-of-magnitude estimate of the cost savings accrued from documented changes to the projects that were generated from constructability reviews. Other acknowledged benefits such as enhanced communication, coordination, quality, or safety were not captured.

A comparison of two formal corporate constructability programs, one within the construction division of a design/construct organization (constructor-performed) and the other within the project management group of an owner organization (owner-performed), revealed different benefit-cost ratios (Russell and Gugel 1993). For the constructor-performed program, the benefit-cost ratio for all projects was 24.3:1, and 21:1 for completed capital projects. The average benefit-cost ratio associated with the owner-performed program was 16:1 for completed capital projects. The researchers identify the large costs needed to operate and maintain the owner's program, as well as the type, size, similarities, and labor-intensity of the facilities constructed, as the reason for the difference in benefit-cost ratios.

These examples encourage CRP implementation and at the same time prompt questions regarding benefit-cost model assumptions. The impressive ratios that have been cited may be significantly changed if a broader range of quantifiable costs and benefits are captured. The study by Russell and Gugel (1993), in particular, indicates an organizational influence.

Research Objectives and Methodology

In light of the foregoing research, the investigators for this study established two research objectives: to identify and address key elements of CRP implementation that seem to have prevented successful implementation, and to produce a model that considers the larger scope of costs and benefits of CRP implementation. This thinking is based upon the notion that the minimization of errors and omissions is a key outcome of the PDP that includes constructability reviews. Here again, the investigators strove for simplicity in order to facilitate CRP implementation. Burdensome record-keeping procedures would discourage adoption of a new process, so the investigators were guided by the objective of minimizing the need for extra record-keeping or tedious data extraction from project records.

The investigators drew upon several sources to conduct the study. The AASHTO *Best Practices Guide* (AASHTO 2000) listed 25 states as having some form of CRP in place. Telephone interviews were conducted of numerous personnel from 21 of these 25 STAs (AR, CA, DE, FL, GA, IN, IO, KS, KY, MI, MO, NV, NJ, NC, OH, OR, PA, SC, SD, WA, and WI). These free-form interviews focused upon identifying the agency's basic approach to constructibility reviews and to confirm the status of their CRP program. A questionnaire was developed and distributed to those STAs that were identified as having some form of active CRP to solicit more detailed information about the CRP. Completed questionnaires were received from five STAs (CA, ME, NJ, NC, OH). Lastly, a follow-up round of phone interviews of the 21 states focused specifically on approaches to involving contractors in the CRP. This survey of STAs helped reveal the resources utilized and common barriers to implementing and maintaining a CRP program.

Concurrent with this survey, a second input to the study consisted of an additional detailed follow-up appraisal of WSDOT's CRP practices in its Northwest Region office primarily for the purpose of gaining insight on the feasibility of alternative approaches to measuring costs and benefits. Toward this end, the investigators examined project records for a handful of selected projects that had undergone constructibility review. Contact with WSDOT personnel was extensive throughout the course of the study and involved detailed discussions and several face-to-face meetings.

A benefit-cost model was developed following the survey and review of the selected projects. Demonstration of the benefit-cost model was accomplished using information from a number of WSDOT projects closed out during the two most recent biennia.

Results

Tracking of CRP Costs and Benefits. Most STAs currently employ methods for monitoring the overall cost and time expended in planning, design, construction, and maintenance of projects. For those STAs that have CRPs, the survey solicited information regarding the tracking of costs and benefits related specifically to constructability reviews. It was found that most STAs currently do not track the costs associated with conducting the reviews nor the benefits resulting from implementing the CRP. California and Washington, which have formal CRPs in place, are states which have made an effort to monitor only the cost and time spent reviewing the projects and conducting the review meetings.

None of the STAs surveyed were noted to perform any type of quantitative assessment of the success of the CRP. All of the personnel interviewed, though, believed that the constructability reviews helped to improve the constructability of their projects. The questionnaire responses indicated that the reviews ranged from “somewhat effective” to “very effective” at improving the constructability of projects. These assessments were made according to the interviewee’s or the questionnaire respondent’s judgment based on their own experience and involvement in the state’s CRP. The following is a summary of the benefits realized from the constructability reviews that were presented by the interviewees and questionnaire respondents:

- Improved communication between functional units, especially design and construction
- Improvements to STA policy and procedures
- Improved STA relations with contractors
- Improved quality of STA contract documents
- Avoidance of major claims
- Saving of time and costs during construction

Measuring CRP Costs and Benefits. The *Best Practices Guide* notes the following observation: “…there appear to be no viable methods developed to date to provide a measure of the success of constructability review programs.” That assessment was the impetus for this study. Measuring CRP costs and benefits requires a distinct CRP implementation with well-defined activities, special attention to documentation, and may include small modifications to an STA's project and payroll accounting systems. However, the measurement procedure is more likely to be performed if it exploits the existing record keeping systems. The investigators recommend a redundant system for documenting CRP costs. That is, costs should be documented as a part of the constructability review documentation and also as a distinct item in the STA's project cost accounting system. The investigators recommend that benefits be measured through use of the standard project accounting records.

The following sections explain the rationale by which the benefit-cost model was developed and present a series of formulas for calculating the benefit-cost (*B/C)* ratios for CRP implementation on both a project and program level. The equations are based upon the proposition that CRP implementation provides efficiencies, when comparisons are made between similar CRP and non-CRP projects, that will result in significant reductions in costs and schedule for planning, design, and construction. The benefits of the CRP for highly unique projects often can be convincingly assessed without a formula and an example is highlighted to make that point.

Identifying Costs of the CRP. The costs of implementing a CRP center around three facets: (1) the people involved and their efforts devoted to the CRP, (2) the tools that are used to conduct reviews and solve constructability problems, and (3) the system and level of support for the program. Figure 1 depicts these facets (shown as success factors) and the specific cost elements that should be documented as constituting the overall cost of the CRP program.

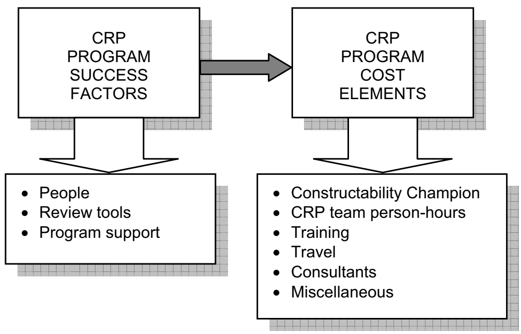

Figure 1. Elements identified for costs of CRPs (Dunston et al. 2005, ASCE)

The Constructability Champion cost element may be either a full time individual or office with CRP development and oversight responsibilities within the STA and is to be distinguished from the CRP team person-hours. The person-hours for reviews constitute the time effort put into the CRP by STA project team members from all of the relevant functional areas within the department. In order to track these hours and costs separately from the regular design engineering costs, project accounting systems should incorporate activity/object work codes established specifically for the time associated with the constructability reviews. These codes, perhaps separate ones for design and construction, should identify time spent in preparation for each review, time spent during the review meetings, and time spent on any added work assignments that result from the reviews. Consultant time (and associated cost) for the CRP should be either added to this item or categorized separately when determining total CRP costs. Distinct CRP travel costs may be incurred for reviews conducted in the field at the site of the proposed project or for those trips made by review participants who may have to travel from other offices to attend review meetings, i.e., bridge, materials lab, etc. CRP team leaders or coordinators must collect this information—the time expended before, during, and after review; payroll classification or hourly rate; and travel expense—at each review milestone and include it in the CRP documentation for the project. Therefore, if personnel fail to conscientiously use the proposed new accounting codes, this data will be available for reconstructing constructability review costs.

The Champion and CRP training constitute the two program level costs for the CRP. Training here refers to that conducted outside the context of a particular project. Such training would be conducted to familiarize or update agency personnel and consultants with the concepts and procedures for CRP teams. Continued program level training would be conducted to establish, maintain, and update the common institutional knowledge of CRP concepts and procedures in the face of normal promotion and attrition of STA personnel. These costs could only be attributed to individual projects through some sort of formula that spreads the costs across the capital projects program.

Not all of these cost elements are significant or even present in every case of implementation, but should be considered as appropriate for inclusion in modeling costs and benefits. The "Miscellaneous" cost element represents a combination of small cost items that includes such things as copying, computing, and transmittals.

Relating Benefits to Measurable Cost Elements. The benefits of the CRP are admittedly not as conveniently measurable as the CRP costs. It is difficult to isolate the effects of other actions and policies, and oftentimes there can only be speculation about "what might have been" had the constructability review not been conducted. That difficulty acknowledged, the model is based upon the premise that there are certain cost and benefit elements that would reasonably be affected by successful implementation of a CRP. Figure 2 depicts the connection made between basic benefits of the CRP and specific project cost elements.

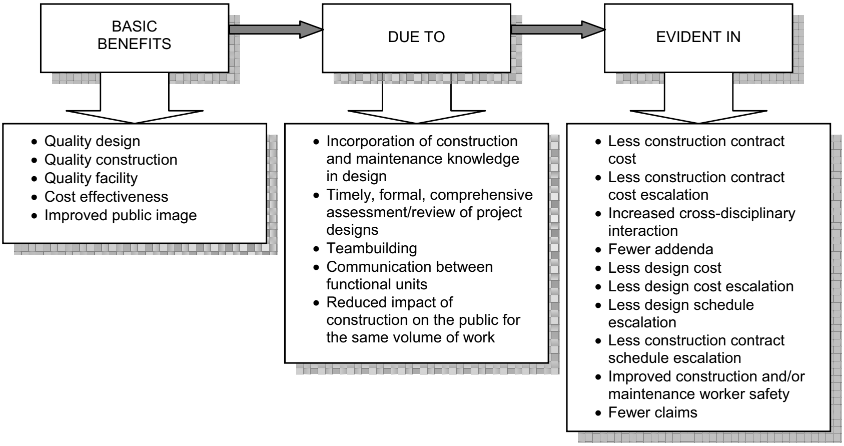

Figure 2. Identification of cost elements related to benefits of the CRP (Dunston et al. 2005, ASCE)

Items shown as basic benefits are related to three primary areas of cost reduction: (1) construction contract and administration costs, (2) planning and design costs, and (3) maintenance costs. Only the first two areas are included in the proposed benefit-cost model. While including maintenance expenditures in the model should be a theoretically straightforward extension, this topic deserves more exploration to make the connection between maintenance costs and design and construction decisions. It should be noted that maintenance costs and benefits resulting from successful CRP implementation are considered, by the investigators, as important as any other costs and benefits in the project life cycle.

All of the “evident in” items, with the exception of team building, are readily quantifiable although not all can be easily represented in monetary terms. Those non-monetary and qualitative indicators of benefit are not included in a benefit-cost model, but should still be recognized as relevant measures of project development performance and success. The next two sections outline the series of equations, which have been developed based on the foregoing discussion, to calculate benefit-cost ratios for constructability reviews.

Benefit-Cost Relationship. The following formula is used to determine the benefit-cost ratio for a CRP as implemented on an individual project:

$$B/C = \frac{\text{Design Related Benefits} + \text{Construction Related Benefits}}{\text{Design Related Costs} + \text{Construction Related Costs}} \tag{1}$$

For simplicity, planning and design are referred to together as design. The benefit, *B*, is generally calculated as the difference between certain definable design and construction costs for a project that has undergone constructability review and the corresponding median costs determined from a pool of projects that are comparable in type and size and have not undergone constructability review. Size is considered a less significant factor than type in selecting comparable projects because virtually the same basic design and construction activities are performed for a type of project regardless of size. While it would be ideal to select a number of comparable projects that satisfies a desired level of statistical significance, it is not likely in many instances that agencies will have large enough numbers of such projects that can be compared on a similar costs basis.

In the following breakdown of the *B* variable, the subscript *med* indicates that the variable represents the median value for the pool of comparable projects and the subscript *i* refers to the specific project for which CRP costs and benefits are being determined. The median value is taken as more representative than the average value because the sample size is always likely to be small and the data cannot be expected to be normally distributed (Siegel 1956; Devore 2000). Also, the median mitigates the effect of projects with extreme values. With these determinations in mind, the design related benefits (DRB) are calculated as follows:

$$\text{Design Related Benefits} = \left(DCE_{med} - DCE_i\right) + \left[\left(DDurE_{med} - DDurE_i\right)\left(Lday_{med}\right)\right] \quad (2)$$

where:

$DCE_{med,\,i}$ = design cost escalation (dollars)
$DdurE_{med,\,i}$ = design duration escalation (days)
$Lday_{med}$ = liquidated damages (dollars per day)

Design cost refers to the STA's initial estimate of project engineering costs for planning and design and constitutes the base amount against which design expense outcomes are compared. Design cost escalation (*DCE*) is the increase in cost beyond the funds initially budgeted, i.e. the final design cost less the initial estimated design cost. Design duration and design duration escalation (*DdurE*) are defined in corresponding fashion. The median value for liquidated damages ($Lday_{med}$) is used as a rate estimate of the cost of delaying the completion of the project, and thus availability of the facility to the public, due to escalation of the design schedule. Each STA will have its own method or scale for arriving at the value for this estimate.

The incorporation of cost and schedule escalation provides a way to acknowledge benefits that would not be captured by simply summing the savings from specific constructability ideas. Reductions in design cost and schedule were listed in Figure 2 as evidence of positive benefits of the CRP. These reductions would be evident in negative escalations of those elements. This fact can be recognized in Equation 2 and is also illustrated in Figure 3.

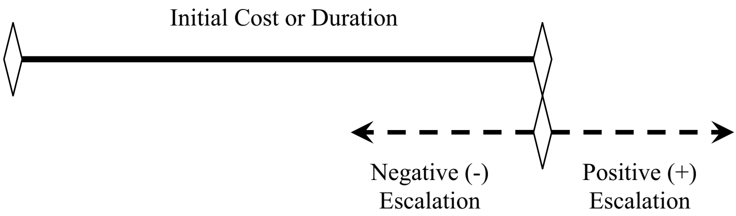

Figure 3. Relationship of changes in cost and schedule and in their escalation

Construction related benefits (CRB) are quantified using the following equation:

$$\text{Construction Related Benefits} = CCCS_i + \left(CCCE_{med} - CCCE_i\right) + \left[\left(CCDurE_{med} - CCDurE_i\right)\left(Lday_{med}\right)\right] + \left(CECE_{med} - CECE_i\right) \quad (3)$$

where:

$CCCS_i$ = construction contract cost savings (dollars)
$CCCE_{med,\,i}$ = construction contract cost escalation (dollars)
$CCDurE_{med,\,i}$ = construction contract duration escalation (days)
$CECE_{med,\,i}$ = construction engineering cost escalation (dollars)

Construction contract cost is the contract award amount. The construction contract cost savings (*CCCS*) refers to the sum of the estimated cost savings associated with documented design alternatives developed through the CRP and incorporated in the final design. In the other studies that were reviewed, this benefit was the only one typically quantified and included in the benefit-cost determination. Such alternatives may be either changes from initial design ideas or deviations from standard designs. They are distinguished from design ideas implemented from the constructability reviews that do not constitute a replacement design, i.e., there is no prior design option for costs comparison. Constructability ideas that create savings might include recommended materials, bridge types, pavement types, traffic control features, types of signs, etc. Also some changes in construction methodology could be incorporated that are less costly than those included in the base estimate. Care should be taken to not include design changes that rightly fall under the heading of value engineering (VE) ideas. The constructability review coordinator should make certain that the cost estimates for constructability ideas are documented along with cost estimates for the design ideas they replace.

Construction contract cost escalation (*CCCE*) is the increase of the construction contract award amount through change orders, claims, etc. Construction contract duration and construction contract duration escalation (*CCDurE*) have corresponding definitions. Construction engineering cost escalation (*CECE*) is the increase in the regular costs incurred during construction, above the budgeted amount, to administer the contract including the cost of engineering associated with changes. The rationale for arriving at this value is the same as that used for determining the design cost escalation. Even though design team personnel may be involved in such changes, their input during the construction phase is customarily documented as a construction cost.

Turning to the denominator of the *B/C* ratio, the cost, *C*, is calculated as the summation of costs incurred by the CRP through all phases of development for the project that is being analyzed. The design related costs (DRC) are summed in the following formula:

$$\text{Design Related Costs} = \text{DHExp} + \text{Travel} + \text{Tools} + \text{Misc\%} \tag{4}$$

where:

DHExp	=	design-hour expenditures; person-hour CRP costs during design (dollars)
Travel	=	costs attributed to field or remote office visits for constructability reviews (dollars)
Tools	=	major costs associated with tools dedicated to constructability reviews such as computer modeling, mock-ups, etc. (dollars)
Misc%	=	miscellaneous; combined cost of minor expenses such as simple computing, record-keeping, copies, transmittals, etc. (dollars)

To complete the *B/C* formula, construction related costs (CRC) for the CRP that are related to construction may be calculated in essentially the same fashion as design related costs:

$$\text{Construction Related Costs} = \text{CHExp} + \text{Travel} + \text{Tools} + \text{Misc\%} \tag{5}$$

where:

CHExp	=	construction-hour expenditures—person-hour CRP costs during construction, including pre-construction and post-construction review (dollars)

For Equation 4, the investigators believe the estimated cost associated with the “Misc%” term is relatively small, about 5-10 percent, or even less of the total design expenses. The “Misc%” item for Equation 5, calculated as a percentage of construction administration and engineering costs, is expected to be less since substantially fewer modifications are expected in the construction phase. Because constructability reviews during the construction phase are rarely practiced, no specific value is recommended here. In either case, project managers should be able to arrive at acceptable estimates for the calculations.

While a *B/C* ratio greater than unity (1.0) clearly signals a positive return on investment for the CRP, even a value slightly less than 1.0 also could be considered positive because, as stated above, there are other indicators of benefit, such as fewer change orders and addenda and avoidance of construction site accidents, that are more difficult to quantify monetarily. The occurrences of these additional items may simply be counted and the totals compared by ratio to each of the corresponding values for typical projects. If contract change orders and addenda are categorized in any way by the STA, then such comparisons may appropriately be made by referring to the changes and addenda that should reasonably be addressed during constructability reviews.

A practical caveat concerning use of equations 1-5 should be noted. First, some of the pooled projects may in some cases have actually received the benefits of unofficial constructability review, especially for high dollar, high profile projects. Therefore, the benefits of the CRP will not be as distinguishable because the reviewed projects will in effect be compared to reviewed projects. As a result, values computed for *B/C* may actually be less than 1. This possibility supports the case for conducting implementation for a representative set of reviewed projects that encompass the range of project types including those that do not customarily get the attention afforded to high profile projects. The resulting individual B/C ratios may be averaged to obtain an indicator that is more representative of the STA's execution of the CRP on its projects.

Benefit-Cost Evaluation for Individual Projects. With the help of agency officials, the research team identified two projects from the Northwest Region of WSDOT which involved at least two constructability review meetings to demonstrate the benefit-cost model. The example projects are: (1) SR20 - Junction Pulver Road Channelization Project valued at $831,252, and (2) SR513 - Montlake Bridge 513/12 Deck Repair and Seismic Retrofit Project valued at $2,633,507. For each of the two case projects, a pool of comparable projects that did not incorporate a structured CRP was identified. A synopsis of each project and the calculations of their benefit-cost ratios are given in Tables 1 and 2 and in Figures 4 through 7, respectively. Figures 4 through 7 specifically present the worksheets designed by the investigators as a guide in performing the calculations. More thorough tabulations of the actual project data, including that from the pooled projects, are documented in an unpublished final report submitted to NCHRP. The case study projects and worksheets are also highlighted in an online brochure available through ASSHTO (Dunston et al. 2002). In each of these cases, there is no dollar amount given for the *CCCS* term since the estimating and documentation of such data was not a part of WSDOT's constructability review procedures.

Both case projects produced a B/C ratio greater than 1.0 (2.29 for Project #1 and 2.10 for Project #2), signifying a positive return on investment for the CRP. In addition to the measurable benefits, STA personnel who participated in the project also relayed additional comments concerning benefits of the CRP. The following are some of the additional benefits observed:

- Early opportunity for designer to explain intent
- Increase in the designer's knowledge of current construction industry practices

- Ability to gather input about the construction site without an official visit
- Reduction in design time
- Opportunity to collaborate with other functions and agencies
- Early resolution of significant problems that may have arisen during project execution
- Opportunity to effect changes that minimize problems during construction and reduce the number of change orders
- Reduction in construction cost by $20,000 (Project #1) and $47,000 (Project #2)
- Opportunity to discuss issues of maintainability often overlooked during design

Table 1. Case 1 - Channelization project (project data)

Project Name:	***SR20 Junction Pulver Road Channelization***	
Contract Number:	005313	
Work Order Number:	OL2535	
Project Description:	Collision reduction project to construct opposing left turn lanes and provide illumination at the SR20 / Pulver Road intersection.	
Project Cost:	$831,252	
Project Duration:	Design:	24 months
	Construction:	39 working days
Responsibility for:	Planning:	WSDOT
	Design:	WSDOT
	Construction:	Strider Construction
Constructability Review Meetings:		
Pre-design Meeting:	8 February 1996	
30% Review Meeting:	7 November 1996	
Comparison Projects:		
005354	JCT SR 536 NB & SB Ramps	
005564	SR 530 NB & SB Ramps	
005671	Useless Bay Road	
005685	116th St NE, NB & SB Ramps	
005899	JCT SE 456th & E of Scatter CR	

CRP BENEFIT/COST WORKSHEET – PART I (Costs)

No.	Cost Item		Costs for Project Reviewed for Constructability ($)
	DESIGN		
1	Design Person-Hour Expenditures for CRP		8,291.43
2	Travel		54.40
3	Tools		0
4	Misc% *(_5_% of design time cost)*		10,464.70
5	**Design CRP Cost (*DRC*)**	*(Sum 1-4)*	**18,810.53**
	CONSTRUCTION		
6	Construction Person-Hour Expenditures for CRP		—
7	Travel		—
8	Tools		—
9	Misc% *(___% of const. admin. time cost)*		—
10	**Construction CRP Cost (*CRC*)**	*(Sum 6-9)*	—
11	**TOTAL CRP COST**	*(5+10)*	**$ 18,810.53**

Notes:

- Design (or Construction) Person-Hour Expenditures for CRP includes all time costs associated with CRP meetings, meeting preparation, and post meeting assignments.
- Travel includes all trips made to the project specifically for constructability reviews and significant travel that is necessary for some offices to participate in CRP meetings, e.g., bridge, materials, etc.
- Tools include major computing expenses for method analysis unique to the project and other construction analysis methods such as solid modeling, mock-ups, or field trials.
- Misc% include all other costs of minor size that are related to support of the CRP such as copies, transmittals, record-keeping, etc.

Figure 4. Cost worksheet for Case 1 - Channelization project

CRP BENEFIT/COST WORKSHEET – PART II (Benefits)

	No.	Item	**A** Median for Pooled Projects	**B** Project Reviewed for Constructability	**C** Factor [$/day]	**D** Difference (A-B)×C [$]
Design Related Benefits (*DRB*)	1	Design Cost Escalation (*DCE*)	$ 54,715	$ 29,294		$ 25,421
	2	Design Duration Escalation (*DdurE*)	0 days	0 days	*(a)*	0
Construction Related Benefits (CRB)	3	Construction Contract Cost Savings (*CCCS*)	—	—		—
	4	Construction Contract Cost Escalation (*CCCE*)	$ 6,434	$ 2,442		$ 3,992
	5	Construction Contract Duration Escalation (*CCDurE*)	0 days	-1 days	*(a)*	$ 1,225
	6	Construction Engineering Cost Escalation (*CECE*)	$8,806	$ -3,623		$ 12,429
	7	**TOTAL CRP BENEFIT**		*Sum (1-6)*		**$ 43,067**

a = median per-day rate for liquidated damages for pooled projects = $ 1,225

Benefit Cost Ratio:

$$B/C = \frac{\text{TOTAL CRP BENEFIT (Section II, line item 7)}}{\text{TOTAL CRP COST (Section I, line item 11)}} = \$43{,}067 \,/\, \$18{,}810.53 = \mathbf{2.29}$$

Figure 5. Benefits worksheet for Case 1 – Channelization project

Table 2. Case 2 - Deck repair and seismic retrofit project (project data)

Project Name:	***Montlake Bridge 513/12 Deck Repair and Seismic Retrofit***	
Contract Number:	005570	
Work Order Number:	OL2964	
Project Description:	Deck Repair and Seismic Retrofit of the Montlake Bridge	
Project Cost:	$2,633,507	
Project Life Cycle:	Design:	21 months
	Construction:	182 working days
Responsibility for:	Planning:	WSDOT
	Design:	WSDOT
	Construction:	Guy F. Atkinson Construction Company
Constructability Review Meetings:		
Pre-design Meeting:	17 February 1998	
30% Review Meeting:	June 1998	
70% Review Meeting:	4 August 1998	
Roundtable Meeting:	28 October 1998	
Comparison Projects:		
005793	N FK Stillaguamish R BR.	
005397	BR. 5/525N-N, 599/1S-S& 509/119	
005527	Spokane St Overcrossing	

CRP BENEFIT/COST WORKSHEET – PART I (Costs)

No.	Cost Item		Costs for Project Reviewed for Constructability ($)
	DESIGN		
1	Design Person-Hour Expenditures for CRP		28,644.00
2	Travel		380.80
3	Tools		0
4	Misc% *(_5_% of design time cost)*		10,350.00
5	**Design CRP Cost (*DRC*)**	*(Sum 1-4)*	**$ 39,374.80**
	CONSTRUCTION		
6	Construction Person-Hour Expenditures for CRP		—
7	Travel		—
8	Tools		—
9	Misc% *(__% of const. admin. time cost)*		—
10	**Construction CRP Cost (*CRC*)**	*(Sum 6-9)*	**—**
11	**TOTAL CRP COST**	*(5+10)*	**$39,374.80**

Notes:

- Design (or Construction) Person-Hour Expenditures for CRP includes all time costs associated with CRP meetings, meeting preparation, and post meeting assignments.
- Travel includes all trips made to the project specifically for constructability reviews and significant travel that is necessary for some offices to participate in CRP meetings, e.g., bridge, materials, etc.
- Tools include major computing expenses for method analysis unique to the project and other construction analysis methods such as solid modeling, mock-ups, or field trials.
- Misc% include all other costs of minor size that are related to support of the CRP such as copies, transmittals, record-keeping, etc.

Figure 6. Cost worksheet for Case 2 – Deck repair and seismic retrofit project

CRP BENEFIT/COST WORKSHEET – PART II (Benefits)

	No.	Item	**A** Median for Pooled Projects	**B** Project Reviewed for Constructability	**C** Factor [$/day]	**D** Difference (A-B)×C [$]
Design Related Benefits (*DRB*)	1	Design Cost Escalation (*DCE*)	$ 2,347	$ 111,000		$ -108,653
	2	Design Duration Escalation (*DdurE*)	0 days	-35 days	*(a)*	$46,585
Construction Related Benefits (CRB)	3	Construction Contract Cost Savings (*CCCS*)	—	—		—
	4	Construction Contract Cost Escalation (*CCCE*)	$ -556	$ -46,557		$ 46,001
	5	Construction Contract Duration Escalation (*CCDurE*)	-9 days	2 days	*(a)*	$ -14,641
	6	Construction Engineering Cost Escalation (*CECE*)	$2,305	$ -110,926		$ 113,231
	7	**TOTAL CRP BENEFIT**		*Sum (1-6)*		**$ 82,523**

a = median per-day rate for liquidated damages for pooled projects = $ 1,331

Benefit Cost Ratio:

$$B/C = \frac{\text{TOTAL CRP BENEFIT (Section II, line item 7)}}{\text{TOTAL CRP COST (Section I, line item 11)}} = \$82{,}523 \;/\; \$39{,}374.80 = \mathbf{2.10}$$

Figure 7. Benefits worksheet for Case 2 – Deck repair and seismic retrofit project

The benefits acknowledged in such comments are critically important, yet not readily apparent from calculating the benefit-cost ratio. Interviews with project participants from design, construction, and maintenance and operations uncovered these and other benefits believed to have significantly contributed to each project's success. These benefits were obtained through the sharing of ideas and experience during the CRP meetings.

It is acknowledged that the CRP may not be the sole reason for a B/C ratio that exceeds 1.0. It is merely asserted by the investigators, and indicated by the proposed formula, that the implementation of a CRP will produce a measurable trend of improved performance in project development. That trend can be ascertained by comparison of reviewed projects against an STA's normal performance in regard to cost categories that would be impacted by the level of constructability.

Evaluating Unique Projects. Projects that are considered unique with respect to type, complexity, and/or the use of innovative design and construction techniques present a problem for applying the benefit-cost model because there are often no similar projects with which to make a fair comparison. These projects are often high-profile, having very high potential for impact to the public, and as a result, receive a high degree of attention during design, especially with regard to constructability. The implementation of constructability reviews then becomes very much continuous, woven throughout the PDP. This level of implementation, wherein the concept of constructability is habitually incorporated in each step of the PDP, should naturally emerge after a formal CRP and an effective training program have been fully instituted and practiced for some period of time. As such, it becomes more difficult to isolate the activities and decisions that may be attributed to constructability "review."

The following description, shown in Figure 8, of the SR-520 Floating Bridge Project in the State of Washington highlights such an example of a unique project wherein much of the costs for incorporating constructability are not easily isolated from the regular project engineering costs, but the benefits are clearly evident in construction cost and schedule.

Constructibility Benefits for the SR 520 Floating Bridge Project

The rehabilitation of the SR 520 floating bridge, a critical link between Seattle and the Eastside, demonstrates an innovative constructibility review process with exceptional results. A storm in 1993 caused severe damage to the bridge, a vital link between two economic centers handling an average of 125,000 daily commuters. In order to fix the present damage and preclude future traffic disruption, the Washington State Department of Transportation (WSDOT) was faced with establishing more stringent performance criteria. Faced with this daunting task, WSDOT enlisted the expertise of KPFF consultants to head the engineering efforts. A constructibility review expert was contracted to join the design collaboration effort along with numerous other subconsultants and contractors. In addition to constructibility discussions during project team meetings, parties participating in the project design routinely considered constructibility in its daily evolution.

The KPFF design called for post-tensioning with 3,600-footlong tendons and 15 post-tensioning strands, a feat never before performed. KPFF and WSDOT collaborated to develop a full-scale mock-up demonstrating the installation process, inviting prospective general contractors to witness the procedure. For a cost of approximately $300,000, this full-scale mock-up reduced the risk to the contractor and WSDOT, and resulted in a construction bid $2.3 million under the engineer's estimate. The collaboration with WSDOT, consultants, and contractors regarding constructibility issues allowed the project, originally budgeted for $20 million, to be completed for $8 million. The innovative tendon design also enabled construction to occur with the minimal traffic impact of only two weekend closures. Finally, the successful rehabilitation deferred the immediate need for an expensive replacement bridge and ensured the long-term viability of this vital transportation corridor.[1]

This example demonstrates the tremendous impact of incorporating both ongoing and scheduled constructibility review procedures early in the design process to affect the success of a complex project. The cost items for constructibility review are difficult to capture beyond the constructibility consultant's fee and construction of the full-scale mock-up, but the greater magnitude of monetary benefits in contract price and the avoidance of negative user impacts speaks for itself.

[1]The Vital Link—Rehabilitating the Evergreen Point Floating Bridge (SR 520), a presentation of KPFF Consulting Engineers, and the Washington State Department of Transportation.

Figure 8. Highlight of a unique project seamlessly incorporating constructability review

Program Level Analysis. After determining that the CRP is beneficial on select projects that have undergone review, an STA may be interested in periodic appraisal of the CRP's contribution to their PDP. Assuming that the agency or regional office has incorporated the CRP throughout its program, the program level benefits of the CRP may be quantified by summing the benefits calculated for each project and dividing by the costs for the CRP program. That evaluation may be made using the following equation:

$$\left(B/C\right)_{program} = \frac{\sum_{i}^{n} Bproject_i + Bprogram}{\sum_{i}^{n} Cproject_i + Cprogram} \tag{6}$$

where:

$Bproject_i$	=	benefits for project *i* as calculated above in equations 2 and 3 relative to a prior period with *n* as the total number of projects during the period under evaluation (dollars)
Bprogram	=	benefits to the STA's project development program such as team-building, improved public image, etc. (dollars)
$Cproject_i$	=	CRP cost for project *i* as calculated above in equations 4 and 5 with *n* as the total number of projects during the period under evaluation (dollars)
Cprogram	=	CRP costs at the program level including the Champion (individual or office) and the ongoing CRP training (dollars)

Two important aspects of using this equation must be noted. First, the calculation of $Bproject_i$ would require identifying pools of non-reviewed projects for comparison in the first program level analysis. However, assuming full adoption of the CRP, subsequent evaluations would compare CRP projects to earlier CRP projects. In this case the *B/C* ratio is likely to be less than 1.0 as the evaluation would in this case be determining incremental benefits from CRP implementation rather than whether the cost justifies the expenditure of resources. Secondly, although the *Bprogram* term theoretically belongs in the equation to represent recognized benefits to STAs, it is presently given a value of zero until an objective method is developed for quantifying such benefits in monetary terms. Monetary benefits for such items as maintainability are appropriate for inclusion, but as stated above, were beyond the scope of this study.

Opportunity Costs. The issue of opportunity costs should be acknowledged. It can be asserted that the time consumed in executing the CRP might be alternatively (and perhaps better) used in moving on to new projects. The investigators counter that argument with the proposition that the gain in efficiency from a properly executed and successful CRP program will save funds that could be applied to possibly even more new projects. The investigators further contend, as indicated in the benefit-cost equations above, that the experience on many projects could also be time saved. The benefits in expected savings of funds and time are tangible programmatic benefits.

The gains from quality, better relationships as well as realizing greater contractual efficiencies with the construction industry, team-building both in-house and with industry, and potential safety benefits in reduced worker and traffic related accidents are significant intrinsic programmatic benefits.

Broader Application and Model Limitations. Although the *B/C* model was developed for application to a state transportation agency's project development process, the general framework of the model and its formulae are transferable to other types of construction. In fact, the model can be used not only to evaluate constructability review implementation in other construction sectors, but with some tailoring, can be applied to any situation where a new process or tool is being added to an existing design process. Such transferability has already been demonstrated by Dunston et al. (2003) where the benefit-cost modeling approach was applied to estimating benefits from integrating Virtual Reality modeling with CAD modeling for design of piping systems in cleanrooms. In that demonstration, Monte Carlo simulation was used to generate sample cost data in the absence of actual project cost data. A key challenge in applying the *B/C* model is to identify the cost data sources.

The chief requirement of the *B/C* model for STAs also limits the broader use of the model, that is, the need to obtain cost data from comparable projects against which to assess the modified project development process. This requirement makes the model most useful for construction consumers who are characterized as being large, regular consumers of construction contracting services and having their own in-house design and construction staff to administer and document costs and schedules for the project delivery process. By having their own staff, such entities are more likely to have the ability to document the specific cost items captured in the *B/C* model. Aside from such owner entities, the next most likely group that may find utility in the model is construction managers, followed by design consultants. The latter, however, may not necessarily retain thorough records of construction contract cost and duration escalations.

The cost of implementing this approach for assessing CRP implementation is minimal. The model was illustrated using data that was already maintained by WSDOT. The task of collecting and maintaining cost data as a part of the record keeping of the CRP adds minimal additional burden to the CRP coordinator and team. In some cases, there may be a one-time cost associated with modifying or adding new activity/object work codes to the computerized STA cost and payroll accounting system.

Conclusions

The following conclusions are made concerning the benefit-cost model that was developed and demonstrated in this study:

- While there is interest among the STAs in determining the B/C ratio for CRP implementation, none currently have an established procedure although most think the ratio is greater than 1.0.

- STA's need to develop their own framework to accurately capture the benefits and costs of constructability reviews. This study recommends incorporating a system with some redundancy in the documentation of CRP costs as a part of the review process and in the creation and maintenance of activity/object work codes that are dedicated to constructability review activities. In addition, cost estimates should be documented for specific constructability ideas that are incorporated into the project design as alternatives to previous design alternatives or standard designs and their associated savings noted. This framework should entail consistent measures to record CRP costs and benefits from all stages of the PDP.
- The B/C model developed in this study can be used to evaluate the success of CRP implementation for any type of project, including those in other construction industry sectors (e.g., residential and commercial buildings, industrial facilities, and other infrastructure projects) as long as a database of comparable projects that have not employed the CRP is available. It measures costs through all phases of the PDP and measures benefits by comparisons between an individual reviewed project and a pool of similar projects that have not been reviewed for constructability. The model is designed to capture benefits that are manifested beyond direct cost savings from constructability ideas. Application of the model demonstrates benefits outweighing costs for the two example projects that were analyzed, and comments by those involved suggest that collaboration between construction and design may produce better contract working day schedules, understanding and identification of critical construction features, and fewer conflicts during actual construction.
- The cost of implementing the proposed *B/C* model is minimal because it is designed to utilize data that should either already be documented or is easily collected and maintained in the CRP documentation. Any necessary changes in accounting system activity/object work codes should constitute a relatively small one-time expense.

Recommendations

The following list of suggestions for future research investigation is recommended. Such studies may be sponsored nationally or may be conducted in-house by specific STAs.

- Perform a study in future years to evaluate the effectiveness of CRP implementation in terms of costs and benefits when more projects have been effectively documented.
- Validate the model (and state CRPs) on more projects of different types. Miscellaneous costs might be more precisely accounted, and costs items not present in the cases analyzed for this study should be further investigated.

- Compare the B/C model (and CRP's) from state-to-state; and from region-to-region within states. Revise the model if necessary. Maybe derive a "type of CRP factor."
- Revisit the idea of a model for unique projects that further addresses the "what if" question and also deals with the continuous form of constructability review.
- Use the B/C model as a tool to explore the optimization of the CRP. B/C ratios less than 1.0 may be more indicative of inefficient constructability review rather than ineffectiveness of the CRP concept.
- Consider the B/C model as a template for analyzing the costs and benefits of any new procedure or procedural modification considered for adoption by an STA or other owner organization with an in-house design unit.
- Conduct a study regarding "if" and "how" the constructability input is recognized by the bidding contractors. Include a survey of the contractors to see if they can provide useful/better data for calculating the benefits.

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The Way Forward: Recommendations for Future Constructability Research and Practice

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A construction project progresses through various stages during its life, from concept development, scope definition, planning, and design through construction, operation, and finally decommissioning. The ability of a project to meet stated goals and objectives in all of these phases is important to the overall success of a project. Constructability, along with operability, maintainability, and recoverability, are project properties commonly considered and managed on a project. The success with which a project team can design a facility to meet stated objectives related to these properties is an indicator of project success.

The papers presented in this special publication describe current research and practice related to constructability in the construction industry. They describe the state of current practice in the industry and current knowledge on the topic, and discuss issues of cost, benefits, contractor input, and constructability review process structure and content. While a significant amount of research on constructability has been conducted, and addressing project constructability is currently included in project delivery processes, additional work is required to more fully understand how to optimize constructability on a project. The following are suggested areas of study to increase our knowledge of constructability and enable design and construction practitioners to improve the constructability of projects.

Constructability in Practice

Determine how constructability is practiced for different project types. While some sectors of the construction industry expend significant amounts of time and effort in addressing constructability, such as the oil/gas and petrochemical sectors, other markets have not. There is a need to identify the level of constructability and the extent to which it is considered in the various construction sectors, e.g., publicly- and

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privately-funded projects; and commercial, residential, transportation, and industrial projects. In addition, research is needed to identify differences in constructability according to: size of design/construction firm, size of project, complexity of project, and location of project. A determination should be made of the extent of consideration, level of detail, resources allocated, methods employed, measurement schemes, and auditing processes employed within each sector.

Investigate constructability internationally. Outside the U.S., many other parts of the world have mature construction industries that we can learn from. It would be useful to know how constructability is considered and managed in other regions such as Europe or Asia, especially if new techniques come to light. A related question is how owners, designers, and builders from different parts of the world address constructability on international projects.

Investigate how constructability is addressed in other industries. Other work industries, such as aerospace, automotive, and shipbuilding, design and construct structures of significant size and expense. Many of the work processes and delivery methods are similar to that in the construction industry. The construction industry can learn from how constructability is considered and enhanced in these other industries.

Constructability Impacts

Identify the characteristics of work processes that are impacted when addressing constructability. Understanding the impacts of addressing constructability on the project delivery process is needed in order to effectively plan, implement, and manage constructability review processes. This knowledge is especially important for firms that are in the beginning stages of implementing constructability review programs.

Identify the economic impacts of constructability efforts and benefits. Creating a successful constructability program commonly requires being able to quantify the value added from constructability efforts on a project. A standard system is needed that empowers constructability task force members to log in their constructability contributions that they have made on a project. This system would be able to track cost and schedule savings that constructability changes have facilitated on a project. Over time this could become a valuable historic record for an organization and the construction industry.

Assess the interrelationship between constructability and other lifecycle properties such as operability and maintainability. Addressing one property on a project may impact, positively or negatively, project performance relative to other lifecycle properties.

Determine the impacts of the level of constructability on life cycle costs, schedule, quality, and safety. Quantifying impacts to other commonly-measured project parameters is needed. While previous research has addressed this topic, further investigation is needed to understand the impacts on projects of various sizes, types, locations, etc.

Constructability Tools and Resources

Develop a guideline for addressing and improving constructability on projects. An industry resource that provides guidance to project teams on suggested practices to improve constructability is currently lacking. A guideline or manual is needed that presents example constructability review processes, provides sample designs that enhance constructability, and describes methods for measuring and evaluating success in enhancing project constructability. The guideline would include types of existing work processes that can benefit from considering constructability, and the cost/benefit model developed by Phillip Dunston, John Gambatese, and James McManus (Dunston et al. 2005) to routinely validate constructability benefits. This would educate and motivate owners to use the guidelines.

Create a database of constructability lessons learned. The fractured nature of the construction industry makes it difficult to transfer knowledge and lessons learned across the industry. However, there are some sectors of the industry which have made great strides in improving constructability. A "clearinghouse" of constructability information would enable access to valuable knowledge that can benefit a project. This effort could begin with the lessons-learned database and software created by the Corps of Engineers and presented in the paper by Jeff Kirby and Bill East in this publication.

Investigate and develop new constructability tools. Continue the research presented in Deborah Fisher's paper by proposing and testing new constructability tools. Use her categories of policy/process-based tools, modeling tools, and technology-based tools. For example, the potential of new technology-based tools such as four-dimensional CAD or building information modeling (BIM) have not been fully realized. This area could also include validation of new constructability software tools.

Education and Training

Bring constructability into architecture and engineering curricula. Current architecture and engineering curricula place significant focus on design, especially with respect to meeting governing design codes. These design codes are often developed with life safety of the end-user as the primary focus. Opportunities to learn about a design's impact on construction are needed to give future design professionals an understanding of and appreciation for the concept. To facilitate this curriculum change, teaching resources are needed that provide instructors with the tools to effectively communicate constructability topics.

Develop and present constructability short-courses for professional development. There is continued need to educate current architects and engineers about constructability concepts. Short-courses should be developed and presented that provide this continuing education. ASCE's Construction Institute should support this effort.

References

Dunston, P.S., Gambatese, J.A., and McManus, J.F. (2005). "Assessing State Transportation Agency Constructibility Implementation." *J. of Const. Engrg. and Mgmt.*, ASCE, 131(5), 569-578.

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