Organizing Constructability Knowledge for Design

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Abstract: Construction contractors have significant constructability expertise to contribute to the design process of projects. To utilize this expertise most effectively, the right information must be made available to the design team at the proper point in time and at the appropriate level of detail. Current methods for utilizing construction knowledge in design have made significant advances to improving projects. However, they are typically rudimentary: unstructured, not very efficient, and rely heavily on reviews. Organizing constructability information according to its use in the design process will allow project teams to take the best advantage of the construction expertise. This paper introduces a model for organizing constructability information based on timing and levels of detail. The model differs from current approaches because of this focus. How the model was developed is described. It is tested on six case study projects to assess applicability on different projects. An illustrative example is provided using a detailed case study of the Pentagon renovation project to show how the model can be used as a metric to guide constructability input during design.

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Introduction

The constructability of a project can have an important bearing on the success of the project (CII 1993). Many of the design decisions made early in the design process affect the construction of the project. Consequently, construction expertise is often incorporated in the design process to improve the constructability of the design.

Despite the importance of constructability input, the means by which this knowledge is introduced in construction projects is still largely rudimentary. Current methods typically use design reviews by construction experts. Sometimes tools, such as checklists, are used to help systematize the process. These methods are relatively unsophisticated, inefficient, and often lead to rework. This, in turn, can result in animosity among team members. While these methods have led to project improvements, it is clear that there have been limited advances in the ways to introduce constructability information more effectively in design.

Common sense and research in the field of knowledge management indicates that the majority of constructability knowledge that exists resides in the minds of construction experts. In order to use this knowledge effectively, the right information should be tapped at the right time and at the appropriate level of detail. Thus, the goal of a system that introduces constructability information to design should be to enable decisions about project design and construction to be made right the first time. When this occurs, constructability knowledge can be most effectively utilized and the process is most efficient.

This paper introduces the Conceptual Product/Process Matrix Model (CPPMM). This model organizes constructability knowledge based on appropriate timing and levels of detail. Relevant literature is reviewed and the development of the model is described. Results of case study analysis are reported that assess the applicability of the model on different projects and show how the model can be used to guide constructability input throughout a project. The constructability metric is also introduced and described. The paper reports on how the model can operate in aiding a project team to identify constructability issues at their appropriate time during design.

Literature Review

The value to project success of incorporating construction knowledge early in the design process has been widely investigated. Paulson (1976), in his seminal study, demonstrated that the best time to influence project costs is early in design. Fig. 1 shows that the ability to influence project outcomes diminishes as decisions are made and the project progresses. The potential advantages of incorporating constructability information early in design have also been documented (Russell et al. 1992; Jergeas and Van der Put 2001). The Business Roundtable (1982) reported a potential return on investment of 10:1. In Russell et al. (1992) case study analysis, savings as much as 10.2% in project time and 7.2% in project cost were demonstrated.

Despite the potential for significant savings, many project teams still struggle with how best to address constructability issues. Only one-half of design firms and 10% of construction companies have a documented constructability philosophy (Uhlik and Lores 1998; Arditi et al. 2002). There seems to be an interest by

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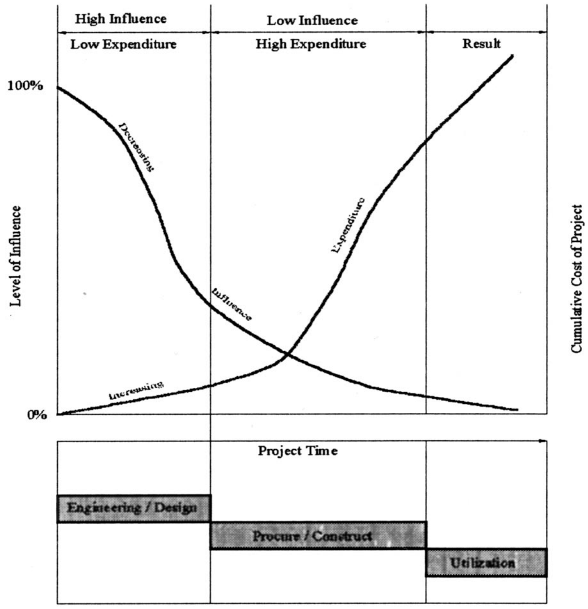

Fig. 1. Level of influence (Paulson 1976)

design firms for enhancing the constructability of their designs. Their efforts are illustrated by the use of some common constructability tools, such as the use of lessons learned, brainstorming sessions, computer models, and physical models. However, the most commonly used practice is still a peer review process. This often results in significant amounts of rework and inefficient design effort, frustration, and conflict between designers and constructors (Arditi et al. 2002).

Efforts to enhance the input of constructability knowledge in design have challenged the industry for some time. Early research work focused on developing methods to improve constructability input during different phases of the project: Tatum (1987) in the conceptual planning phase; O'Connor et al. (1987) in the engineering and procurement phase; and O'Connor and Davis (1988) in field operations with the use of innovative construction methods. When combined, this work shows that different constructability issues had to be addressed at different phases of the project. This was an important development.

The Construction Industry Institute (CII) developed a constructability program designed around the presumption that constructability input needed to be an ongoing process throughout the entire project (CII 1993). A feedback loop of lessons learned was an essential part of the process. Seventeen core concepts were established, eight of which are applicable to the design phase. To make the tool useful, each concept was then related to an activity on the program and to the project development schedule where it could be applicable. An Application Matrix was developed that identifies which concepts are applicable at which phases of the building process (CII 1993). While it is useful to understand which generic concepts can be applied at each phase, further assessment is necessary to understand the type of information required to support design decisions. General concepts are only relevant when they can be grounded in a specific application. Additionally, no methodology was provided to organize lessons learned according the appropriate phase of the project.

Understanding the design process and knowing what information is required for specific design activities are important to effectively utilize constructability knowledge in design. Austin et al. (1999) developed a modeling software program to categorize information flows between activities in design. The model enables designers and constructors to successfully integrate and plan their work based on information demands. A significant part of the integration is improving the quality of information passed between stages, using the right people and doing so at the right time. The flow of constructability information between stages of projects is an important element of this process but this is a characteristic that has not received enough attention in past and present research.

The availability of the right information at the appropriate level of detail is needed to effective utilize constructability knowledge in design. Fisher and Tantum (1997) used this concept as a basis to develop five categories of constructability knowledge. They proposed an expert computer model that could "check the constructability of structures on demand, similar to what spell and grammar checkers do for text." Hanlon and Sanvido (1995) developed a classification scheme for constructability information which highlights the key attributes of constructability information. This scheme uses the groupings identified by Fisher and Tantum (1997). While this classification system is useful for database entry and retrieval by keyword searches, it does not provide any link to phases in the design process or any insight into input timing. What is needed to advance the effective use of constructability knowledge in design is a model that describes both types of information needed and timing of that input.

The study of knowledge management (Polanyi 1962; Nonaka and Takeuchi 1995; Inkpen and Dinur 1998; Cook and Brown 1999; Liebowitz 1999) reveals that expertise, such as constructability knowledge, exists in two different forms. Information that can be articulated in written form, such as guidelines and rules or thumb, is referred to as *explicit knowledge*. Knowledge that exists only in the heads of experts (technical skills, intuitions, and insights) is referred to as *tacit knowledge*. This is an important distinction because tacit knowledge cannot be articulated in written form and easily transferred from one individual the next, yet it is often the most valuable type of knowledge (Nonaka and Takeuchi 1995). In the field of knowledge management and organizational cognition, it is widely accepted that approximately 80% of what individuals know is in the form of tacit knowledge (Nonaka and Takeuchi 1995). Remarkably, for constructability knowledge, Hanlon and Sanvido (1995) confirmed this percentage, reporting that the source of 83% of constructability knowledge is not written down in any form, but lies in the heads of experts. The literature review revealed no research attempts that focused on developing methods to tap and utilize expert (tacit) constructability knowledge. The key to utilizing this tacit knowledge effectively lies in the ability to organize constructability knowledge according to the level of detail it represents and its application in the design process.

Conceptual Product/Process Matrix Model

Opportunities for savings and streamlining projects exist at every phase of project development. An appropriate level of detail of information must be provided at each phase of the project to take greatest advantage of these opportunities. Consequently, the organization of constructability information is critical. To improve the use of constructability knowledge, the CPPMM was developed as a tool to organize constructability information for design (see Fig. 2). As shown in Fig. 3, the model draws together two existing models. The first of these models is the *Product Model Architecture* (PMA). This model arranges different levels of building in-

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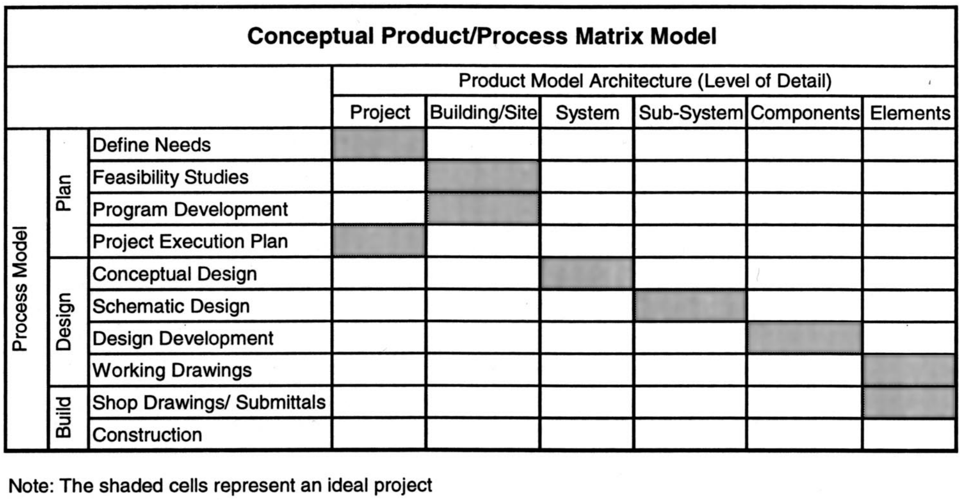

Fig. 2. Conceptual Product/Process Matrix Model

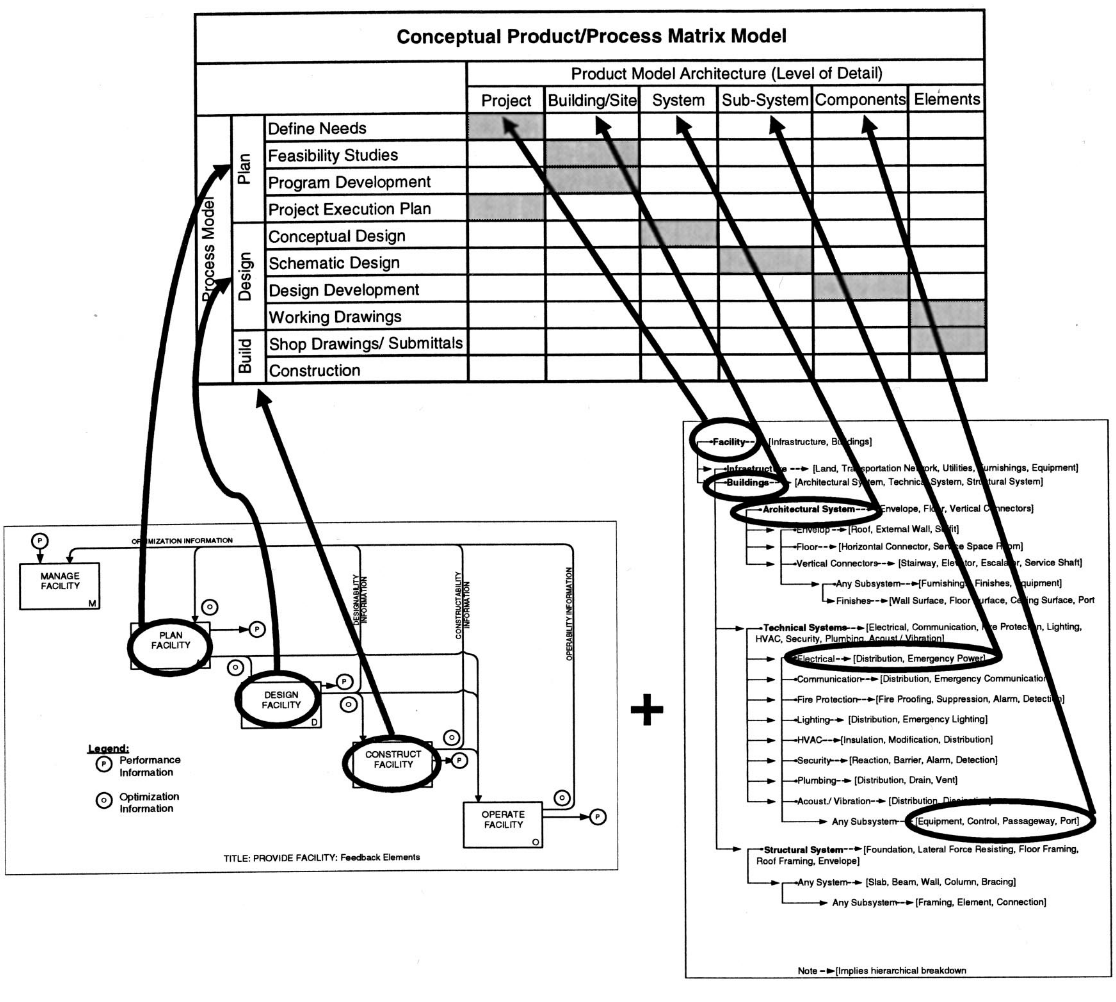

Fig. 3. Development of the Conceptual Product/Process Matrix Model

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Table 1. Levels of Detail on Construction Projects

Level of detail	Description	Constructability example
Building/site level		
Building/site level	Defines buildings, land, and infrastructure within a facility (roads, electrical utilities, communication, water utilities, gas utilities, lighting, waste removal, and site conditions).	Design buildings to follow the natural contours of the land instead of excavating the land to suit the building.
System level		
Defines selection, sizing, and order of operations of each system		
Architectural systems	Space allocations, net and gross area, finish material types, life safety requirements, energy guidelines, loading restrictions.	Prefabricated smartwall system used to improve space flexibility, reduce, material waste and ease of installation.
Technical systems	Design criteria, code requirements, system types, available fuel sources, power requirements.	Fan-powered induction units allow return air to be taken directly from occupied space thus reducing amount of ductwork by half.
Structural systems	Load assumptions, structural system type, materials available, soil characteristics.	Use tunnel formed cast-in-place concrete in lieu of masonry or precast concrete to reduce labor intensity.
Subsystem level		
Defines subsets of building systems		
Architectural systems	Envelope, floor, vertical connectors.	Provide access to mechanical rooms for maintenance from corridors to eliminate disturbance to tenant space.
Technical systems	Electrical, communication, fire protection, lighting, heating, ventilation, and air conditioning, security, plumbing, acoustic/vibration.	Create specific zones for all above ceiling work in standard areas (e.g., hallways, standard office space) for each discipline (e.g., electrical, IT, security).
Structural systems	Foundation, structure, envelope, roof.	Foundations should be designed as shallow systems (e.g., spread footings) rather than deep systems (e.g., piles) where possible to minimize ground penetration in unknown site conditions.
Component level		
Defines individual pieces of subsystem		
Architectural systems	Roof, external wall, soffit, service, space, room, stairway, elevator, escalator, service shaft, ceiling height.	Design the sloped curtain wall so that it is glazed from the outside.
Technical systems	Heating, ventilation, and air-conditioning distribution, emergency power/communications/ light, fire proofing, suppression system, alarm, detection, insulation, drainage system, venting system, gas system, fuel supply.	Relocate generator to basement to simplify installation and reduce a distribution network.
Structural systems	Slab, beam, wall, column, bracing, footings, piles, retaining walls, pile driving.	Eliminating unnecessary bearing plates and replace with precast panels.
Elements (part) level		
Describes the pieces of components		
Architectural systems	Wall surface, floor surface, ceiling surface, port, finishes, furnishings, equipment, cabinets, permanent shelving, door, window.	Horizontal metal channel under curtain wall was preassembled to structural beam to simply coordination and sequencing.
Technical systems	Equipment, control, passageway, wires, switchgear, terminal units, piping, monitor devices, signal equipment, actuators, air handling unit, terminal units, distribution ductwork, building, main, risers, branches, fixtures, sprinkler system, extinguishers, cable trays, pull boxes, expansion joints.	Use aluminum electrical feeders instead of copper to reduce material cost and ease material handling.
Structural systems	Framing, element, connection, footing concrete, footing rebar, cast piles, pile caps.	Setscrew fittings were used for conduit connections in lieu of compression fittings for quicker assembly.

Note: After Sanvido (1990), Sanvido et al. (1992) and Hanlon and Sanvido (1995).

formation in a hierarchical structure to organize the vast quantity of available data on a building (Sanvido et al. 1995). The second model is the *Integrated Building Process Model* (IBPM). This model outlines the key processes and decisions made at each phase of the project delivery process (Sanvido et al. 1990). As with the first model, the IBPM is a systematic organization of information. By combining the separate models, connections can be established between levels of detail of constructability information and project phases. Hence, *the purpose of the CPPMM is to organize constructability information to allow the right information to be made available to the project team at an appropriate level of detail and at the proper phase of design*.

In the CPPMM, information is organized by levels of detail and by the project phase in which information is required. The CPPMM is structured as a matrix so that constructability information can be organized according to the level of detail (columns) and the project phase (rows) (see Fig. 2). The x axis of the matrix uses the Product Model Architecture to indicate levels of detail, and the y axis uses project phases defined in the IBPM to indicate project phases. Table 1 demonstrates how different detail levels are defined in the CPPMM. When matched with information about timing, the model provides a structured organization of constructability ideas and guidance as to these ideas should be engaged in the project.

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Shaded areas in the matrix (see Fig. 2) indicate the ideal project phase and level of detail at which issues should be addressed. These shaded areas are defined by the structure of the model. However, depending on the unique requirements of individual projects or delivery systems employed, the locations of these shaded areas could be adjusted. For example, they could be moved earlier on a fast track project. Analytically, the shaded areas can be used to evaluate whether constructability ideas are being addressed at the right level of detail and at the right phase of the project. Issues classified below the ideal boxes are presumed to be addressed too late, and those above too early.

Conceptual Product/Process Matrix Model Example

An example will help to describe the CPPMM. The following example pertaining to the selection and detailed design development of the structural system illustrates the different levels of constructability detail and how each is connected to a design decision which is addressed at a particular phase of the project.

At the "Building/Site" level, information regarding soil conditions and location of existing utility lines are important constructability factors in determining the type of structural system selected. This information is needed to perform the planning functions (feasibility studies and program development). During conceptual design, the type of structural system is selected. Constructability information, such as advantages/disadvantages of structural systems and availability/skills of the local labor market, is an important consideration at the "System" level. The next level of detail, "SubSystem," aligns with the schematic design phase and represents constructability information pertaining to framing layout and spacing of the structural members. The "Component" level correlates with decisions addressed during design development such as the standard sizing of structural members and use of flying forms for slab construction. The final level of detail is the "Element" level which represents constructability considerations, such as standard/simplified connection details and standard size structural members. This level of detail is addressed during the working drawing and shop drawings/submittal phase of a project.

Case Study Analysis

Having introduced and explained the basis for CPPMM, the paper now describes the results of testing performed to show how the model is used. A case study approach was chosen because this method enables the most effective evaluation of how the model should be used (Yin 1994). A two-part approach was adopted as follows.

1. *Test for Applicability:* Empirically test the ability of the model to capture and organize constructability input across multiple projects using a descriptive case study analysis.
2. *Perform Detailed Case Study:* Illustrate by experimental implementation how the model can be used to guide constructability input in a project.

Test for Applicability: Multiple Case Study Analysis

A descriptive case study investigation using six projects was undertaken to test the ability of CPPMM to capture and organize constructability input on different projects.

Empirical data in the form of constructability improvements were gathered from six contractors on five design-build projects via interviews with the project manager and a design review by the construction manager. The types of projects included in the study were a research office building with a parking structure, a 100,000 sq ft data center, a sports stadium addition, a manufacturing/support facility, and a prison complex. All projects used a design-build delivery method. Interviews were performed addressing the question, "How did you (the contractor) influence the design of the project?" Using IBPM nomenclature, each constructability issue was then assigned by the respondent to the phase of the project corresponding to when the issue was addressed.

The investigation identified a total of 77 constructability issues. This data set was created from the specific ideas identified by the respondents in the interviews. For the issues to be included in this data set, each had to have a material impact on the project cost, schedule, quality, efficiency, or intensity. Having satisfied this test, the issues were categorized into their appropriate level of detail using the PMA classification system. The classification of the data was verified by the research team to assure correct interpretation of the system by the respondents. Each constructability issue was then plotted on the CPPMM matrix (Fig. 4) according to the phase of the project assigned by the subject and the level of detail denoted by the PMA.

The results revealed that 40% (31 of 77) of the constructability issues identified were addressed at the proper point in time according to the CPPMM. 36% (28 of 77) were addressed too late. 23% (18 of 77) were addressed too early. All of the constructability issues were straightforwardly classified into the model. Broadly, the results suggest that even savvy contractors do not always provide timely constructability input during design. Importantly for the purposes of testing the CPPMM, the results also demonstrate the ability of the model to capture and organize data over different types of projects thus indicating the applicability of the model.

Detailed Case Study: Pentagon Renovation Project

A detailed case study was performed on the Wedge 1 Pentagon Renovation Project to illustrate how the model can be applied to an ongoing construction project to guide constructability input in the project. This project was delivered using a design-bid-build project delivery strategy and was an ideal application for such a study due to the longevity of the project and high repetition of design. Benefits and lessons learned from the study could be used to help guide further renovation projects.

The data collection process employed multiple techniques including a full document review of all change orders, requests for information, submittals, and lessons learned information, as well as conducted interviews with the general contractor and major subcontractors. The purpose of the data collection process was to identify specific constructability issues that arose on the project and document the phase of the project in which they were addressed. The ideas were then subjected to a filter: An issue was classified as a constructability issue if it had a material impact on the project schedule, quality, efficiency, or intensity (e.g., simplify ductwork transitions).

The research team was on site for three months. They attended foreman meetings and other activities which provided a detailed understanding of the project. Interviews were conducted with the project team leader, architect, construction managers, project managers, superintendents, foremen, estimators, and field managers. Bias was reduced in the research by the research team working directly for the owner, the Pentagon Renovation and Con-

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Conceptual Product/Process Matrix Model

Process Model		Product Model Architecture (Level of Detail): Project	Building/Site	System	Sub-System	Components	Elements
Plan	Define Needs						
	Feasibility Studies						
	Program Development						
	Project Execution Plan						
Design	Conceptual Design						
	Schematic Design				1		
	Design Development			5	8	26	18
	Working Drawings					6	4
Build	Shop Drawings/ Submittals						
	Construction				2	5	2

Note: The shaded cells represent an ideal project

Fig. 4. Part 1 research results

struction Program Office, rather than any contractor. This arrangement allowed access to all project documents including sensitive pricing information.

The analysis identified 52 constructability issues, 44 of which were implemented on the project. Each issue was classified according to its appropriate level of detail using the descriptions in Table 1. Using the timing information obtained through data collection, the 44 implemented constructability issues were then plotted on the CPPMM (Fig. 5). Constructability issues were considered to be addressed too late in the process if they were plotted below the ideal (shaded) boxes on the model and too early if it was plotted above the ideal boxes.

A sample of the type of data collected is shown in Table 2. Three constructability issues are provided along with the corresponding level of detail and project phase identified by the project team. As indicated in Table 2, the first issue was identified too late during the project and this resulted in additional costs ($35,000). The second issue was identified during the appropriate phase of the project and avoided extra costs ($20,000) during construction. The third issue was identified too early according to CPPMM yet still avoided a cost of $200,000. The procedure valuing the costs of identified issues is explained below.

The results indicate that 23% (10 of 44) of the issues were addressed at the ideal phase of the project, 7% (3 of 44) were addressed too early and 70% (31 of 44) were addressed too late. This information provides a snapshot of the major constructability issues encountered on the project and when they were addressed. Plotting constructability issues on the CPPMM provides the project team with a measure of how effective they have been at identifying issues at their appropriate time. The more issues that fall within the shaded cells, the more effective the project team is at addressing constructability concerns in a timely fashion. When issues are plotted too early, unnecessary time is spent discussing and evaluating them and when issues are addressed to late, rework often occurs and opportunities to realize cost and schedule savings are diminished.

To illustrate the significance of identifying constructability issues at the appropriate time, the issues plotted outside the shaded

Conceptual Product/Process Matrix Model

Process Model		Product Model Architecture (Level of Detail): Project	Building/Site	System	Sub-System	Components	Elements
Plan	Define Needs						
	Feasibility Studies						
	Program Development						
	Project Execution Plan						
Design	Conceptual Design					1	
	Schematic Design					1	
	Design Development			2	1	2	1
	Working Drawings					3	3
Build	Shop Drawings/ Submittals				1	2	5
	Construction			1	1	7	13

Note: The shaded cells represent an ideal project

Fig. 5. Pentagon Wedge 1 conceptual product/process matrix model results

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Table 2. Sample Data Collection

Issue	Phase	Level	Estimated cost
1. Use spread footings in lieu of pile caps to minimize soil penetrations.	Design development	Subsystem	$35,000 Additional cost
2. Stack all utility rooms.	Design development	Component	$20,000 Cost avoidance
3. Sections of terazzo floors could be refinished instead of replaced.	Shop drawings/submittals	Element	$20,000 Cost avoidance

cells were investigated further. The costs associated with design and construction rework, extra coordination, scheduling or staffing necessary to integrate the constructability issue into the project were identified. These were costs that could have been avoided if the issue was addressed at the proper time. Rough order of magnitude estimates of construction costs were developed using three primary data sources: (1) project cost data (i.e., from project records like change orders), (2) the owner's estimating team, and (3) the researchers' knowledge of the project. The study found that an estimated $3,490,000 could have been avoided by identifying the 31 (late) constructability issues at their appropriate time.

Valuable constructability insights were unearthed by this analysis. One such issue concerned the design of the wet stack piping which occurred at eight locations about the building. The original design called for tapered transitioning from 3 in. (75 mm) to 2.5 in. (60 mm) to 2 in. (50 mm) as the stack extended up the building (Fig. 6). These transitions were causing significant excess field work and errors. Consequently, the design was changed to a 3 in. (75 mm) pipe with no transitions. Based on the change order costs, the savings for addressing this issue at the proper time could have been as much as $782,000. This does not include the actual costs associated with excess field work and errors incurred prior to the change order approval. In other words, while these costs were included in the change order they were omitted for valuing the issue had it been addressed at the right time. Consequently, the project was only able to achieve approximately one-half of this level of savings because it was discovered during construction. This issue was plotted on the CPPMM at the element detail level and at the working drawings phase. Importantly, the decision was taken into consideration during the design of Wedge 2 of the Pentagon renovation.

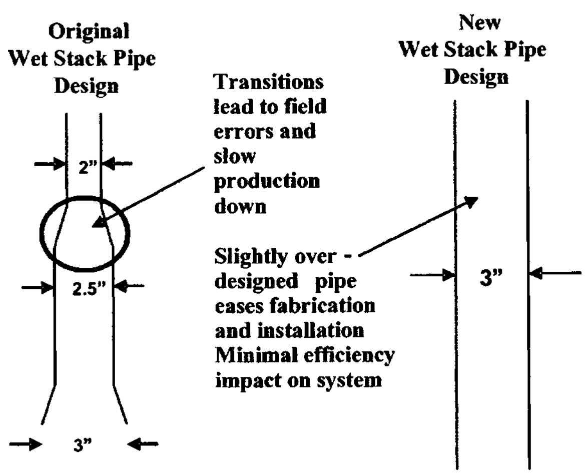

Fig. 6. Wet stack design

Constructability Metric

The CPPMM is intended to help guide constructability input throughout a project. As a metric, the model can be used to gauge whether the project team is addressing constructability issues at the appropriate detail and appropriate phases of the project. For example, the data from the Pentagon case study, which were plotted in Fig. 5, can be transformed into a simple metric indicating the proportion of issues addressed too late, too early, and at the appropriate time. Fig. 7 shows the constructability metric for this project. This plot clearly shows how effective the team is at addressing constructability issues at the appropriate detail and time.

In this metric form, the CPPMM has two main functions. First, the metric can be used as a measure of success at the end of the project, as illustrated in the Pentagon case study. Second, and perhaps more usefully, the metric can be applied throughout a project as an in-process metric after each major phase. For example, a list of constructability issues identified during design development can be assigned their appropriate levels of detail, plotted on the CPPMM and graphed using the constructability metric. This would provide feedback to the project team on how effective they were at addressing constructability issues and learn to perform better. Over the course of a project, team members would develop their understanding of the types of constructability issues that should be addressed at each phase of the project.

Utilizing Constructability Knowledge

The results of the case study analysis indicate that the CPPMM is applicable across different projects and capable of capturing and organizing constructability input. The research showed how the model can be used as an assessment metric to gauge how well project teams are addressing constructability issues at the appropriate time to maximize the savings potential.

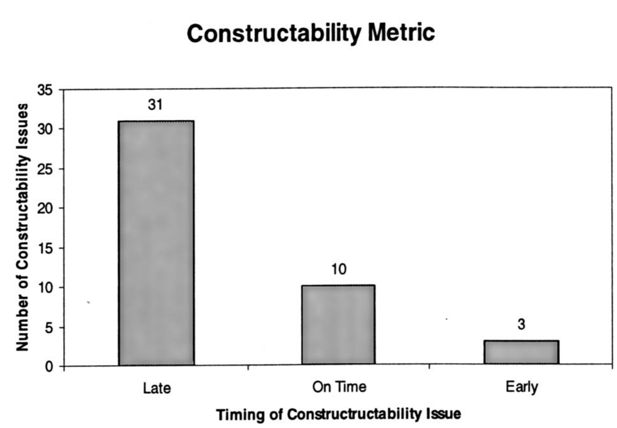

Fig. 7. Constructability metric with case study data

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As was noted in the literature review, approximately 80% of constructability knowledge exists in tacit form. This knowledge is located in the heads of industry experts (i.e., construction managers, and superintendents). Despite many attempts to do so, this knowledge is very difficult to write down or incorporate into an expert computer database system. Extracting this knowledge at the appropriate point in time during project design is a key element to effectively utilizing constructability expertise. The organization of constructability information according to its relevant design phase is the first step to developing a process for tapping the abundance of constructability expertise in the people of this industry.

The application of management and organizational cognition research provides some insight into how to better utilize constructability (tacit) knowledge in design. Cook and Brown (1999) state that "explicit knowledge can be used as an aid to help acquire tacit knowledge," while Weick (1995) suggests that "extracted cues are crucial to evoking action." Extracted cues (explicit knowledge) can help trigger a cognitive connection with tacit knowledge. In the context of constructability knowledge, extracted cues can be represented by design rules or guidelines which can be introduced to stimulate an individual's tacit knowledge or expertise. The evoked constructability expertise can then be applied to the design decision. *The key to accessing constructability expertise is introducing the right information at the right time and in the right level of detail*. This reinforces the importance of the CPPMM to improving the use of constructability knowledge in building projects.

Methods for utilizing the full potential of constructability expertise from all sources (including specialty contractors) exist in the development and refinement of integrated/collaborative design mechanisms, such as planning charrettes and design workshops. For example, the constructability issues identified by the CPPMM that apply to a specific design phase could provide a point of focus for the design team to address at a workshop or design charrette at the beginning of each design phase. In other cases, the model could be used to advance certain design criteria, such as sustainability objectives.

Industry Implications

The ability to link the level of detail of constructability knowledge to a particular project phase has significant research implications as well as practical applications. The approach provides industry with a useful mechanism to organize constructability issues or lessons learned according to level of detail and the phase of the project where it should be addressed. Numerous constructability issues are typically documented throughout the course of a project, but rarely are these stored as lessons learned. If they are, they are almost never stored according to their appropriate timing on a project. This model allows organizations to review their current set of constructability issues or begin documenting issues and classifying each according to their appropriate timing. This is useful when performing future reviews because the project team can reference this database of constructability issues and understand exactly what types of issues they should be addressing at each phase. This is a skill that typically takes construction experts many years to develop.

An example of how constructability information can be straightforwardly organized according to different levels of detail is illustrated in Table 1. Summaries of the descriptions for each level of detail are provided along with corresponding constructability examples. All examples except for one (Building/Site Level) originate from this research analysis. Table 1 provides a clear description of the criteria necessary to: (1) organize constructability information for design according to the different levels of detail; and (2) apply the CPPMM to any project.

The constructability metric can be applied at each major phase of a project to gauge how effective teams are at addressing constructability issues. This can be very valuable information, especially for owners who understand the importance of properly utilizing constructability knowledge in design.

An advantage of the CPPMM is that it links constructability rules to different stages of building design in a step-by-step format. This will allow research on more advanced methods to organize and utilize constructability knowledge. The model can be used to expose specific information requirements necessary to progress design, and thus be used to improve the quality of information flow across design stages. Constructability issues often stretch between multiple disciplines and require multidisciplinary teams to effectively address the concern (Austin 1999). The CPPMM can be used to frame a focused collaborative design workshop or charrette in order to help project teams share individual knowledge and take maximum advantage of available expertise.

Future Research

In this paper, an initial study was undertaken to explain and confirm the importance of linking the levels of detail of information to particular phases of the project. To effectively utilize constructability knowledge in design, the right information must be available at the right time, in the right level of detail, and from the right entity. Further research is needed to develop the information repositories at each phase of design. Further study will provide a clearer understanding of what types of information are useful at each project phase and populate the cells in the CPPMM. The universal nature of the CPPMM means that it can be extended to help manage information on other important project issues, such as maintainability, safety, sustainability, and value engineering.

A key component to properly addressing constructability, not examined in this research, is the human interface aspect of organizing constructability input for design. Further research is needed to determine how best to extract constructability knowledge from general contractors, specialty contractors, and suppliers at each point of the design process. The simple introduction of a contractor at different points in design is not enough to take full advantage of their expertise. Neither is performing design reviews sufficient. Further research must address how to overcome differences between designers and contractors, and engage project participants in the design process to optimize constructability input. Future research should address how designers would best receive and use information and test sophisticated methods, such as automated computer programs (i.e., "pop-ups") during design activities.

Conclusions

This research introduced a method to organize constructability information according to timing and levels of detail. A relationship between the level of detail of constructability information and the project phase was introduced, and CPPMM was presented. The ability of the model to capture and organize construc-

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tability issues was tested. A detailed case study provided an illustrative example of how the CPPMM could be used to aid the project team to improve the input of constructability knowledge on projects. The constructability metric was introduced as a method to measure how effective project teams are at addressing constructability issues in timely manner. The results confirm the value of CPPMM to improving constructability input, and show that more research needs to be performed to improve the introduction and use of constructability knowledge in design.

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References

Arditi, D., Elhassan, A., and Toklu, C. (2002). "Constructability analysis in the design firm." *J. Constr. Eng. Manage.*, 128(2), 117–126.

Austin, S., Baldwin, A., and Wasket, P. (1999). "Analytical design planning technique: A model for the detailed building process." *Des. Stud.*, 20(3), 279–296.

Business Roundtable. (1982). "Integrating Construction Resources and Technology into Engineering." New York.

Construction Industry Institute (CII). (1993). "Constructability implementation guide." *CII Publication 34-1*, Austin, Tex.

Cook, S. D., and Brown, J. S. (1999). "Bridging epistemologies: The generative dance between organizational knowledge and organizational knowing." *Org. Sci.*, 10(4), 381–400.

Fisher, M., and Tantum, C. B. (1997). "Characteristics of design-relevant constructability knowledge." *J. Constr. Eng. Manage.*, 123(3), 253–260.

Hanlon, E., and Sanvido, V. (1995). "Constructability information classification scheme." *J. Constr. Eng. Manage.*, 121(4), 337–345.

Inkpen, A. C., and Dinur, A. (1998). "Knowledge management processes and international joint ventures." *Org. Sci.*, 9(4), 454–468.

Jergeas, G., and Van der Put, J. (2001). "Benefits of constructability on construction projects." *J. Constr. Eng. Manage.*, 127(4), 281–290.

Liebowitz, J. (1999). *Knowledge management handbook*, CRC, New York.

Nonaka, I., and Takeuchi, H. (1995). *The knowledge creating company*, Oxford University Press, New York.

O'Connor, J., Rusch, S., and Schulz, M. (1987). "Constructability concepts for engineering and procurement." *J. Constr. Eng. Manage.*, 113(2), 235–248.

O'Connor, J., and Davis, V. (1988). "Constructability improvement during field operations." *J. Constr. Eng. Manage.*, 114(4), 548–564.

Paulson, B., Jr. (1976). "Designing to reduce construction costs." *J. Constr. Div., Am. Soc. Civ. Eng.*, 102(4), 587–592.

Polanyi, M. (1962). *Personal knowledge-Towards a post critical philosophy*, Routledge and Kegan Paul, London.

Russell, J., Gugel, J., and Fadtke, M. (1992). "Benefits of constructability: Four case studies." *SD-83*, Construction Industry Institute, Austin, Tex.

Sanvido, V., et al. (1990). "An integrated building process model." Computer Integrated Construction Research Program, University Park, Pa.

Sanvido, V., et al. (1995). "A process-based Information Architecture." *36*, Computer Integrated Construction Research Program, University Park, Pa.

Tatum, C. B. (1987). "Improving constructability during conceptual planning." *J. Constr. Eng. Manage.*, 113(2), 191–207.

Uhlik, F., and Lores, G. (1998). "Assessment of constructability practices among general contractors." *J. Archit. Eng.*, 4(3), 113–123.

Weick, K. E. (1995). *Sensemaking in organizations*, Sage, Thousand Oaks, Calif.

Yin, R. (1994). *Case study research design and methods*, Sage, Thousand Oaks, Calif.

J. Constr. Eng. Manage., 2005, 131(8): 911-919