Constructability Information Classification Scheme

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Abstract: This paper discusses the development and testing of a generic model that classifies constructability information for reinforced-concrete structural elements. It identifies decisions and factors affecting constructability and classifies them in a constructability information model (CIM). This model is tested with concepts from the literature and an industry survey. A refined structure is developed and evaluated for future work. The resulting CIM is a hierarchical breakdown of constructability concept attributes grouped in categories and subcategories. The major categories include design rules, lessons learned, external constraints, resources constraints, and performance information. Each concept is further classified by associating it with the facility processes and products that it affects. The CIM is found to be useful within the limits of its testing; reinforced-concrete structural elements. Further classification refinements are required to improve information storage and retrieval efficiency.

INTRODUCTION

The process of integrating constructability information into the early stages of facility planning and design varies significantly. At one end of the spectrum, team members who are construction experts, systematically provide feedback on design and planning alternatives. At the other, owners and designers develop detailed drawings and specifications with little or no consideration for how the facility will be built. Research has shown that on projects where construction impacts are considered in the planning and design phases, substantial cost- and time-savings can be achieved (Paulson 1976; "More construction" 1983; Tatum et al. 1986).

It is recognized that the integration of construction information in the early phases of a project provides the best opportunity for cost- and time-savings. To integrate this information effectively and efficiently, it should be organized in a format desirable to its users and follow a logical development process. While several researchers have developed single user classification systems for constructability information, none provide a comprehensive structure for all project phases (Tatum et al. 1986; O'Connor et al. 1987; "Constructability" 1987; Boeke 1990; Fischer 1991).

OBJECTIVES

The present paper describes the development and testing of a model that classifies constructability information for use by designers or constructors throughout all phases of construction. Specific steps in the research were:

- To identify the key decisions requiring constructability information and the corresponding factors that influence constructability assessment
- To develop an information model that categorizes the factors and classifies the decisions, known as the Constructability Information Model (CIM)
- To test and refine the CIM

RELEVANT LITERATURE

The research discussed in this article is a summary of that presented in Hanlon (1993). In that report, Hanlon reviews the research in the areas of constructability, product models, and facility information architectures. The adopted definition of constructability was that of the Construction Industry Institute ("Constructability" 1986). They defined constructability as "the optimum use of construction knowledge and experience in planning, engineering, procurement, and field operations to achieve overall project objectives."

Four topic areas in constructability research were identified and reviewed: need recognition, benefit and demand determination, guideline development, and information collection and classification. Need recognition research identified that constructability knowledge integration is essential during the early project phases. Research in benefit and demand determination attempted to quantify the returns from implementing constructability programs. In general researchers agreed that the benefits can be significant. Most of the research in constructability improvement has been in guideline development. Here, programs are devised to facilitate the integration of constructability knowledge.

Contributions in the area of constructability information collection and classification include: Fischer (1991), preliminary design of reinforced concrete structures; Boeke (1990), reinforced concrete walls, columns, foundations and footings; Touran (1988), concrete formwork design; O'Connor et al. (1987), engineering and procurement of electrical, instrumentation, piping, and structural work; Tatum et al. (1986), prefabrication, preassembly, and modularization; and Hanna (1989) construction rules for selecting vertical and horizontal formwork systems.

The classification systems developed by these researchers to store their information vary significantly. Tatum et al. (1986), Boeke (1990), and Touran (1988) stored the information in a text guideline or rule-of-thumb format. O'Connor et al. (1987) used three categories for each information element titled: concept, analysis, and specific applications. Fischer (1991) used five categories: application heuristics, layout knowledge, dimensioning knowledge, detailing knowledge, and exogenous knowledge. "Guidelines for Implementing a Constructability Program" (1987) suggested a data sheet to track construction knowledge, which had the following elements: date, project title, summary, key words, disciplines, locations, savings, and discussion.

Tatum (1988) developed a classification system for construction technology. Information about construction technology is an important subset of constructability knowledge as indicated by its definitions. Tatum's system is centered on construction processes (methods and tasks). Associated with a construction process element are three other elements: materials and permanent resources, construction applied resources, and project requirements and constraints. The at-

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tributes associated with each of these elements play a strong role in this research.

In the area of construction technology, Ioannou and Liu (1993) have developed the Advanced Construction Technology System (ACTS). This system provides classification of new technologies based on the Construction Specification Institute's CSI Masterformat in a database with keyword searching. Each entity has 25 fixed attributes related to the product's design, construction, operation, and maintenance. Such a system overlaps this research for constructability concepts whose improvement comes from the introduction of a new technology.

To improve constructability, a better method is needed to capture and transfer experience from engineering and construction projects to future projects (Tatum 1987). Several researchers have taken steps toward this goal. Fischer's (1991) work was implemented at a detailed level and tested, but primarily captured the constructability concept's impacts on design. Tatum (1988) and Ioannou and Liu (1993) both have similarly implemented and tested models, but they were designed to store construction technologies. They both have attributes appropriate for constructability but are not sufficient. Tatum does not include experiences or lessons learned, which form a significant part of constructability assessment. Ioannou and Liu's (1993) attributes appear very general and do not include resources necessary to achieve the results. CII ("Guidelines" 1987) tracked lessons learned but excluded the impacts on design, resources, performance, and the external. It appears that no research provides a comprehensive model for constructability information.

Based on this review of classification systems, a set of goals was established for a comprehensive constructability information model.

- It should be able to store any technology or experience related information in a retrievable form to the user.
- It should handle concepts needed for any process which requires constructability knowledge; this includes management, planning, design, and construction.
- It should be capable of linking to any product classification or coding system; this flexibility will ensure usefulness in any country or discipline.

Popular product models and facility information architectures were reviewed to select a benchmark for constructability model compatibility. The Process Based Information Architecture (PBIA) (Sanvido 1990) was chosen.

CONSTRUCTABILITY INFORMATION MODEL (CIM)

Goals

The CIM is a framework through which constructability information can be classified, stored, and retrieved accurately and efficiently throughout the project. The goal for the model was to define the attributes or characteristics that best store a constructability concept.

Scope

The model was tested for reinforced concrete structural systems and components only. This scope was selected for two reasons. First, there is a significant amount of experience and technology data already collected by researchers, including: Fischer (1991), Boeke (1990), Touran (1988), and Hanna (1989). Second, reinforced concrete, due to its numerous applications, spans a large variety of constructability concepts.

Development of the CIM

The first step in defining constructability information was to obtain a comprehensive list of possible attributes from the literature and interviews with industry experts. By grouping like attributes, information categories were formed. These were then tested and refined using constructability concepts previously gathered in the literature. Based on the modified structure, a survey was developed and administered to industry experts. The survey retrieved case examples of constructability concepts in the format of the CIM structure. Analysis of the survey results enabled finalization of the model structure and classification scheme. The scheme was developed by categorizing constructability concepts by the processes (methods and sequences) and products (systems and components) that they affect.

CIM Structure

Discussion on the final CIM structure is divided into two parts. First the categories of information and their associated attributes are presented. Then the storage format of the attributes are discussed.

Categories and Attributes

The structure includes five major categories, two of which are further divided into subcategories as shown in Fig. 1. Four of the categories, design rules, performance, resource constraints, and external impacts, describe the requirements or impacts of a concept if it is to be used. A fifth category, lessons learned, provides a historical record of relevant experiences. Following is a description of each category and its attributes with examples.

Design Rules. Design rules incorporate the impacts that a concept has on design. The attributes of this category are based on the work of Fischer (1991). The first attribute, design applicability, is different than the other three. Its purpose is to indicate thresholds of economic usefulness for a concept based on design. For example, use of flying forms for slabs is only economical when the building is at least six stories high (Fischer 1991). The remaining attributes describe constraints or suggestions for design if the constructability concept is to be used. They include rules on design layout, dimensions, and details. For example, a concept on forming concrete columns might include a suggestion for details to chamfer corners for improved quality and durability.

Performance. Performance includes properties of a concept that describe or impact construction performance. It is divided into two subcategories: results and impacts.

Results include those attributes that describe the performance of the concept. They include cost, production rate, quality, and safety. These attributes include relative descriptions of the concept's performance compared to others that could produce a similar product. According to survey respondents, this information usually provides the major influence for choosing one concept over another. These attributes were found to be significant to the model through the course of the research.

Impacts describe the direct and indirect influences on a concept's performance. Direct impacts include concept complexity, basic method type, and activity interdependency. Indirect effects on performance include: level of automation, primary construction location, the fundamental process of the concept, and concept uncertainties. The separation of the attributes into these two levels of impacts resulted from the survey. This category of attributes was largely derived from the work of Tatum (1988).

Lessons Learned. Lessons learned is interpreted several ways by industry and the literature. Some may contend that

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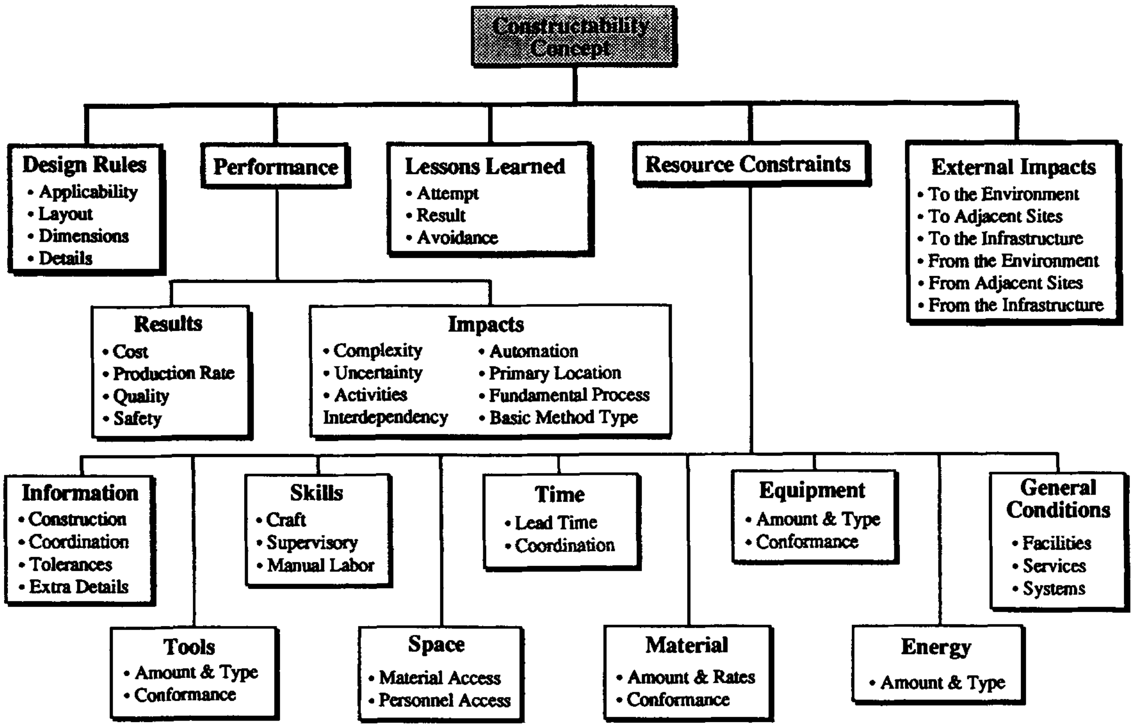

FIG. 1. Categories and Attributes of Information for Constructability Concepts

all of the attributes included in the CIM are part of a lesson learned. Here, however, a representation closer to that of CII ("Guidelines" 1987) has been adopted. Its final form was influenced by Ed DiTomas, Vice President of Turner Construction Company (Edward DiTomas, personal communication, Turner Construction Co., New York, N.Y., 1993). This definition includes general information about a project, a description of the attempted improvement, the corresponding result, and suggestions for future problem avoidance.

For example, consider a concept to use precast concrete slabs. One lesson learned could be from a project experience where off-site stock piling of the slabs was used instead of just in-time delivery. The result may have been costly due to the time and energy spent on rehandling. To avoid this in the future, stock piling might not be a preferred method, and if it were to be used, a material handling plan might be desired. Handling lessons learned in this manner enables one unique storage point for a concept such as using precast concrete slabs, but allows flexibility to attach multiple experiences to the single concept.

Resource Constraints. Resource constraints describe the resource requirements or impacts for concept use. It is divided into nine subcategories based on resource type as shown in Fig. 1. The majority of the attributes in this category were derived from the work of Tatum (1988). The attribute categories are: information, skills, equipment, tools, general conditions, space, energy, material, and time.

Information describes the types of information and the detail required to achieve concept implementation. The attributes include information on construction, coordination, tolerances, and extra details. Consider the example used previously about precast concrete slabs. Such a concept will have significant increases in tolerance, and extra detail information that needs to be documented. These increases would be to accommodate the required mechanical, electrical, and plumbing penetrations that must be made at the precasting site.

Skills describe the amount and type of craft, supervisory, and manual labor skills required. For instance, using self-climbing forms requires a high level of qualified supervision for the concept to be successful (Fischer 1991).

Equipment includes the amount and major type of construction equipment used and a description of how this equipment compares with industry standards. Self-climbing forms for architectural finish concrete for example, are most times custom built, as was the case for the Tabor Center in Burkhart (1987).

Tools are similar to the equipment category. This category describes amounts and major types of construction tools used, with a comparison to industry standards.

General Conditions describe special facilities, services, or systems that are required or impacted by the use of a concept. On-site preassembly of rebar cages for instance, may require an additional facility such as a make-up area. The facilities attribute of general conditions includes site space required for the construction activity.

Space deals with the resulting access for materials and personnel to the work face. Certain concepts, like self-climbing forms, severely reduce work-face access for people and materials. The space required for a concept is included in the general conditions facilities attribute.

Energy describes the amount and type of energy used for a concept. In most cases this category does not vary significantly. However, there are circumstances where a concept may have unusual needs. For example, pouring winter concrete without accelerators can require significant space heating for proper curing; using power wrenches to speed metal formwork construction requires compressed air.

Material describes the amounts, types and delivery rates required for the major construction materials. This category also contains an attribute describing how the materials conform to industry standards. Slip forming operations for example, require a very reliable and steady supply of concrete. In some locations such a supply may not be feasible without building a nearby batch plant.

Time describes lead or preparation time and activities coordination time for a concept. Using custom-built self-climbing forms, for instance, requires lead time for their design

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and construction as well as time to train the crew on their use. This attribute does not include time information related to the actual construction, that is covered in the performance category. Here it refers only to how a concept impacts time for management, planning, and design processes. That includes the management and planning during construction.

External Impacts. External Impacts include impacts to and from external sources if a concept is implemented. This category's inclusion was largely influenced by Smith (1993). A concept's use is sometimes very dependent on its impacts to and from the environment, adjacent sites, and the infrastructure. For example, using slurry foundation walls has a significantly lower impact on adjacent sites than driving sheet piles. Such an attribute can be very desirable when there are adjacent structures at risk during construction.

Attribute Format

The attributes of the model have two formats. One provides a place for free-form description. The other adds a numerical rating, ranked between 1 for the best to 6 for the worst. This rating ranks the concept's condition for the specific attribute relative to other concepts that produce the same product. A clear example is the cost attribute in the performance category. If one concept has a better unit cost than another, it will have a lower rating. The main purpose for the ratings is to provide an efficient way to retrieve the concepts in the future. One drawback of ratings that should be noted, however, is that they require periodic updating as new technologies become available. Also, the person providing the ratings must define some basic measurement standards.

The attributes for design rules and lessons learned have only textual descriptions. All resource constraints and external impact attributes include ratings. Performance result attributes all include ratings but some performance impact attributes do not. Ratings were omitted from attributes when the author felt they did not have a meaningful purpose.

Concept Classification

After the attributes and categories are established, a meaningful way to identify concepts is required, namely a classification scheme. It is clear from the literature and industry surveys, that people describe constructability knowledge in terms of the product being constructed and the processes affected. This relationship is shown in Fig. 2. This shaded area uniquely defines a class of concepts that one might wish to review. A query for instance might be: provide the schematic design (a process) constructability knowledge for structural floor-framing slabs (a product). Since each person defines construction processes and products a little differently, a standard should be followed.

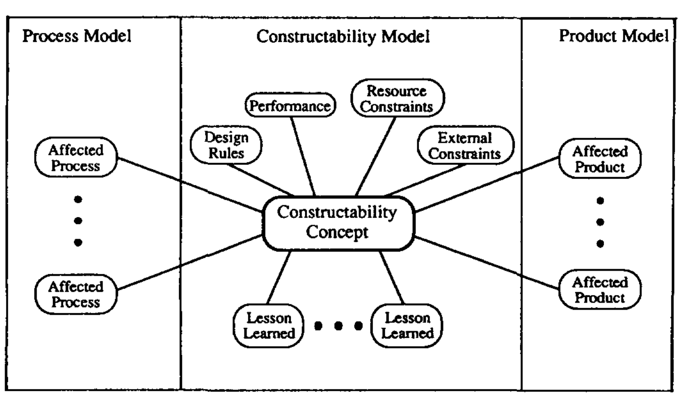

FIG. 2. Classification of Constructability Concepts

The Integrated Building Process Model (IBPM) (Sanvido et al. 1990) provides a standard for facility processes. The IBPM processes which use constructability information are listed in Table 1. The process names in parentheses are those more commonly used by industry.

There are several good product classification standards currently available. As described in Hanlon (1993), the Product Model Architecture (PMA) (Khayyal and Sanvido 1990) attempts to provide a comprehensive structure for integration in a facility information architecture. To test the CIM, the revised PMA shown in Fig. 3 was used.

In addition to the affected processes and products, a concept has several other attributes that are useful for querying purposes. The concept title, description, and lessons learned attributes have been selected for word searches. For example,

TABLE 1. Process Classifications for Constructability Knowledge [Adapted from Sanvido (1990a)]

Process type (1)	Process name (2)
Management	Develop facility management plan
Planning	Develop program
Planning	Develop project execution plan
Design	Understand functional requirements
Design	Explore concepts (conceptual design)
Design	Develop system schematics (schematic design)
Design	Develop design (design development)
Design	Communicate design to others (working drawings)
Construction	Select work methods
Construction	Estimate work
Construction	Schedule work activities

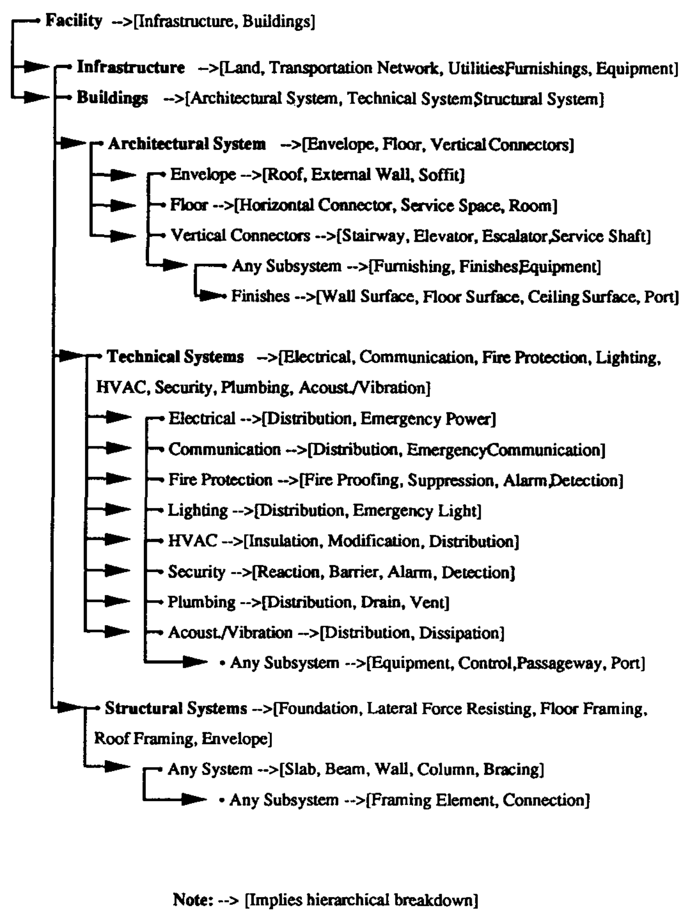

FIG. 3. Revised Product Model Architecture

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a concept about concrete self-climbing forming methods should have "climb" and "form" somewhere in the concept title or description and possibly a specific application like "chimney walls" in the lessons learned. This method assumes a full-text search is used. The alternative and preferred method (Blair and Maron 1985) is a keyword search. Defining and testing keywords requires a significant collection of data and is beyond the scope of this research. It is however highly suggested for future research.

TESTING

To test the model, constructability concepts from the literature and a survey of industry experts were used to populate the model. Concepts from the literature primarily dealt with construction methods and sequences and constructability programs. Concepts for programs dealt mainly with contracts, meetings, and project procedures to promote the integration of construction method and sequence knowledge into early project phases. The attributes describing programs were very different from those of methods and sequences. This research focused on the latter.

The results of the survey were analyzed in several ways. The concepts were categorized according to the decisions (processes and products) for which they might be required. The CIM classification scheme was compared to these categories and modified based on the results. Patterns in the data were used to determine attribute relationships and eliminate those considered unimportant. The source and availability of concept information was used to confirm that a CIM-based data repository is feasible and useful.

Analysis of the survey results showed that constructability issues related to more than just methods and sequences. Issues were also found relating to design details, dimensions, layout, sequence, and construction location. The results of the survey also established an importance ranking for each attribute for a given constructability idea. These rankings varied, however all attributes were determined to be meaningful.

TABLE 2. Survey Participants

Survey identification No. (1)	Survey participant (2)
1	Lehrer McGovern Bovis, general superintendent
2	McCarthy, Project manager
3	Southland Industries, vice president
4	Omni Construction Inc., project manager—concrete division
5	George Hyman Constr. Co., director of engineering
6	Hensel Phelps, superintendent
7	Warner Construction Consultants, manager, project management division

Survey Overview

Survey participants classified and documented constructability concepts using the CIM. The survey first established the credibility of the participant by obtaining a sample of their constructability experience. Second, it retrieved feedback on the CIM attributes and classification scheme through a detailed documentation of several concepts. A sample of the survey concept documentation can be found in Appendix I. Third, it provided an opportunity for general commentary on the CIM. Each participant was interviewed before, during and after the survey to ensure the CIM was interpreted properly. Tables 2 and 3 summarize the participants and cases of this survey.

There were seven survey respondents with a total of 20 constructability concepts. One respondent with three concepts described heating, ventilation, and air conditioning (HVAC) systems to test the flexibility of the model. The other 17 concepts focused on reinforced-concrete systems.

Process Categories Affected by Constructability Information

The processes affected by the constructability improvement were identified for each concept from the descriptive information provided in part 1 of the survey. The corresponding processes in the model are summarized in Table 4. The names in the column "Process impacted by surveyed concept" of Table 4, do not match the model names exactly because they describe an output of the process, not the process name itself.

These results clearly indicate that concepts affect more than just construction methods and sequences as first postulated

TABLE 3. Overview of Survey Cases

Survey identification No. (1)	Case No. (2)	Project type (3)	Project phase concept used (4)	Item being addressed (5)	Concept (6)	Savings result (7)
1	1	Hotel	Value engineering	Slabs	Filigree slabs	Time/money
1	2	Dormitory	Value engineering	Slabs	Lift slabs	Time/money
2	1	Desalination plant	Construction planning	Weirs	Two piece design	Time/money/quality
2	2	Parking garage	Blank	Architectural facade	Precast on-site	Time/money
2	3	Arts center	Blank	Retention basin	Bored hole with pipe	Time/money/feasibility
3	1	Biomedical	Working drawings	Mechanical systems	No grandstanding	Productivity
3	2	Medical center	Working drawings	Mechanical systems	Drawing overlays	Time/rework
3	3	Medical center	Working drawings	Ductwork	Field fabrication	Material handling
4	1	Office/residences/parking	Construction submittals	Foundation walls	Form without weld	Money
4	2	Office/residences/parking	Change order	Slabs	Cast in place from steel	Time/money
4	3	School/parking	Working drawings	Seams and joints	Rotate detail	Time/money/sequence
5	1	Office	Working drawings	Column size	Standardize size	Time/money
5	2	Medical center	Construction submittals	Platform slab	Composite design	Feasibility
5	3	Archives	Construction submittals	Waffle slab	Easier details	Easier forms
6	1	Water treatment plant	Daily construction	Inverted key	Easier details	Easier forms
6	2	Water treatment plant	Daily construction	Slab on grade	Dimension	Time/money
6	3	Water treatment plant	Design development	Clarifiers	Post tension to CIP	Time/money
7	1	Apartments	Working drawings	Column shear head	Eliminate table form	Time/money
7	2	Office	Design development	Column layout	Smaller beam	Money
7	3	Office/parking	Working drawings	Elevated slab	No post tensioning	Time/money

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TABLE 4. Summary and Assignment of Affected Processes for Surveyed Concepts

Process in model (1)	Process impacted by surveyed concept (2)	No. of surveyed concepts found in this category (3)
Develop facility management plan	—	0
Develop program	—	0
Develop project execution plan	—	0
Understand functional requirements	Design Sequence	1
Explore concepts (conceptual design)	—	0
Develop system schematics (schematic design)	Construction Material	1
	Design Layout and Dimensions	Up to 4
Develop design (design development)	Design Layout and Dimensions	Up to 4
	Design Details	Up to 8
Communicate design to others (working drawings)	Design Details	Up to 8
Select work methods	Construction Methods	6
	Construction Location	1
Estimate work	—	0
Schedule work activities	Construction Sequence	1

from the literature. They also provide evidence that the IBPM processes (Sanvido et al. 1990) can be used for concept identification. Of the 11 processes found to be affected by constructability information, the survey of 20 concepts identified six of these. Also, no other affected processes were found outside the list of 11.

In Table 4, "design details" is identified with both "design development" and "working drawings" processes in the model. This is done because the distinction from one process to the next is a function of scale. Depending on the scale of the concept's impact, it will affect one process or the other. The same issue exists for "design layout and dimensions" with the "Schematic Design" and "Design Development" processes in the model. The number of surveyed concepts found for a category includes the overlapping concepts, resulting in the "up to" designation.

Relative Importance of Attributes

The second analysis on the survey results was to determine whether certain attributes were more important for concepts affecting like processes. Such knowledge could be used to highlight these attributes during data storage and retrieval for greater efficiency.

Each survey respondent ranked each attribute for its relative importance in achieving the constructability improvement described. By grouping the improvements according to affected process, patterns in these importance ratings could be analyzed. Using visual inspection of these groupings it appeared that no such patterns existed. It is possible that with significantly more data, patterns may become evident. However, it is concluded for this research, that attributes are not uniquely associated with constructability improvements affecting a specific process.

Ranking of Importance of Attributes

The third analysis on the survey data was to determine the relative importance of attributes for all surveys, and to eliminate any that were deemed unimportant. This step was intended to minimize the number of attributes and establish precedence for data storage/retrieval.

TABLE 5. Survey Results—Attributes Ranked by Total Importance

Attribute category (1)	Attribute name (2)	Rating[a] (3)	Rank (4)
External constraints	From infrastructure	0	Low
External constraints	To environment	2	Low
External constraints	From environment	2	Low
External constraints	To adjacent sites	3	Low
Resource constraints	Energy used	4	Low
Performance	Quality	5	Low
Performance	Safety	8	Low
External constraints	To infrastructure	9	Low
Design rules	Design layout or arrangement	9	Low
External constraints	From adjacent sites	10	Low
Resource constraints	Amount or type of facilities required	11	Low
Performance	Automation	12	Low
Performance	Uncertainty	12	Low
Resource constraints	Tools used	13	Low
Performance	Fundamental process	13	Low
Performance	Primary location of construction operation	14	Low
Resource constraints	Material required	16	Low
Resource constraints	Tool conformance	17	Low
Design rules	General design applicability rules	17	Low
Resource constraints	Amount or type of supervisory skills	18	Low
Design rules	Design detail	18	Low
Resource constraints	Amount or type of services required	19	Low
Resource constraints	Material conformance	19	Low
Performance	Basic type of method	20	Low
Resource constraints	Equipment conformance	21	Medium low
Resource constraints	Amount or type of manual labor	24	Medium low
Resource constraints	Amount or type of systems required	24	Medium low
Resource constraints	Tolerances	24	Medium low
Design rules	Design dimension	24	Medium low
Resource constraints	Personnel access	30	Medium low
Performance	Complexity	31	Medium low
Resource constraints	Information required for construction	32	Medium low
Resource constraints	Amount of preparation or lead time	33	Medium low
Resource constraints	Equipment used	35	Medium low
Resource constraints	Information coordination	39	Medium low
Resource constraints	Amount or type of craft skills	42	Medium high
Resource constraints	Amount of activities coordination time	42	Medium high
Performance	Interdependency with other activities	43	Medium high
Resource constraints	Redesign or extra details	44	Medium high
Resource constraints	Material access	61	High
Performance	Relative production rate	63	High
Performance	Relative cost	72	High
Lessons learned	Lessons learned from past experiences	80	High

[a]Rating is the sum of the importance values for all survey responses.

For each attribute, the total importance rating for all survey cases was summed and tabulated. Each concept had a maximum of a 12 rating per attribute. This maximum would occur if it was essential for achieving the resulting improvement for the "system-method," "system-sequence," "component-method" and "component-sequence." For 20 concepts, this yields a total of 240 as the highest possible attribute rating.

A ranking scheme for the resulting distribution was established based on straight percentiles. The maximum rating

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TABLE 6. Summary of Survey Response Frequencies for Attribute Information Source, Availability and Format

Response (1)	No. of responses (2)
(*a*) Source	
Expert	189
Company	27
Industry	13
(*b*) Availability	
Always no	13
Usually no	27
Usually yes	142
Always yes	47
(*c*) Format	
Picture	5
Drawing	79
Text	146
Numeric	30

found was 80. This established quartile ranking thresholds based on ratings of 20, 40, and 60. The resulting rankings were sorted and are shown in Table 5.

For those attributes ranked low (0–20 ratings), only one (impacts from the infrastructure) had zero responses. In general, the "external impacts" category had low rankings. Three cases found the category important. All of these cases impacted the construction method. This accounts for half of the cases affecting construction methods. Although it might be possible to remove "impacts for the infrastructure" as an attribute without losing information, the limited survey sample suggests it should remain.

Although "quality and safety" are ranked low, it is likely that they actually rank much higher. They were added to the attribute list at the suggestion of a participant and were only included in the final two surveys, one of which found them to be of importance.

Overall it was concluded that, based on the sample size and varying importance ratings, no attributes should be eliminated. In addition, the data suggests that the "performance impacts" category may have two levels of attributes based on importance. The primary or more important impacts appear to be "complexity," "activities interdependency," and "basic method type."

Constructability Information Sources, Availability, and Format

The final analysis of survey data identified the attribute information sources, their availability, and their format. The results of this analysis help to confirm feasibility and usefulness of a CIM data repository and determine future data storage requirements. Data on these characteristics was surveyed for each attribute. The frequency of participant responses for each category was then summarized as shown in Table 6. This frequency was calculated by totaling the survey responses for each source, availability, and format category. With 43 attributes per survey and 20 concepts, the maximum possible frequency is 860. From the results, it is apparent that most constructability information results from experts who are usually readily available. This supports the usefulness and feasibility of maintaining this type of data, expert knowledge, and experience. The results also show that information can usually be captured with text or drawings; however, other storage formats were used.

CIM USES

There are two uses envisioned for the CIM. The first is to develop a stand-alone database using its structure. The database would be useful for storing and retrieving only constructability knowledge. This research explored this use as discussed in Hanlon (1993).

The second use is to integrate the CIM structure in a comprehensive information architecture, enabling both a historical database and project-specific databases. The latter would link constructability concepts considered, used, and generated on a project to the project data itself. This use has been identified as area for future research.

Both of these uses would be valuable to entry-level engineers as a learning tool or to project managers who have not had experience with a specific reinforced-concrete detail. The system can be used by estimators or even by designers and construction managers providing preconstruction services to a project.

COMPARISON OF RESULTS TO OBJECTIVES

The first objective was to identify the decisions made during facility development that rely on constructability information. The key decisions requiring constructability information were identified as the processes of the IBPM (Sanvido et al. 1990), which use optimization information as a constraint. Specific constructability decisions relate to unique process and product elements. The factors that influence constructability assessment were found to include both experience and technology issues.

The second objective was to develop an information model to classify key constructability decisions and factors identified previously. A subobjective was to make this model compatible with current research in process and product modeling to allow for future integration. The resulting CIM structure had five major categories of information: design rules, lessons learned, resource constraints, external constraints, and performance. A hierarchical breakdown of subcategories and attributes organized the information considered for constructability assessment. Attribute format included text fields and a rating system. Each constructability concept was classified by the decision processes and products that it affected. Further distinction of concepts was achieved through word associations in specific attributes.

The third objective was to test the CIM with the opinions of industry experts. The CIM process categories were found to be consistent with those from industry concepts, however, examples for all categories were not found. Attributes were found to not have a unique association with constructability improvements affecting a specific process. It was shown that the information of certain attributes is more important than others. However, the limited survey sample suggested all attributes should remain in the model.

AREAS FOR FUTURE RESEARCH

Four areas related to the CIM should be considered for future research. The first is further testing and refinement of the CIM. Current testing suggests that the attributes and their names may need to be modified for clarity. Products other than concrete structural systems should be included.

Second, the accuracy and effectiveness of concept retrieval should be further evaluated. The use of keywords should be studied to determine if they provide for better concept classification. The use of keywords in place of more specific process and product breakdowns should be considered. The issue of data-entry flexibility for keywords compared to free-form text should be included. The Advanced Construction Technology System (ACTS), a system to store construction technologies by Ioannou and Liu (1993), should provide a starting point for evaluating keywords.

Third, operability and maintainability attributes should be

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Did the Constructability Improvement Require Changes to These Factors?

Construction Optimization Factors (1)	Changes required? (2)	Type of change (3)	Importance[a]				Source[b] (8)	Availability[c] (9)	Format[d] (10)
			System		Component				
			Method (4)	Sequence (5)	Method (6)	Sequence (7)			
Information Resources[e]									
Information Required for Construction (i.e., the overall amount of information required to define and perform the construction operation)	yes no		0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3	E C I	0 1 2 3	P D T N
Information Coordination (i.e., relative amount of information which needs to be coordinated for construction success. For example, slip forming has a high degree of progress coordination required between rebar, forming and placement activities. Other types of information coordinated could include: fabrication, operations, or specifications)	yes no		0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3	E C I	0 1 2 3	P D T N
Tolerances (i.e., relative influence of drawings, codes, configuration, etc., on construction. For example, post tensioning requires accurate cable placing information to meet design intention)	yes no		0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3	E C I	0 1 2 3	P D T N
Redesign or Extra Details (i.e., relative amount of design information required to define the construction method and perform the work.)	yes no		0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3	E C I	0 1 2 3	P D T N
External Impacts									
To the Environment (e.g., hand built forms generate a large amount of waste)	yes no		0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3	E C I	0 1 2 3	P D T N
To Adjacent Sites (e.g., driven pile foundations can disturb foundations of adjacent structures)	yes no		0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3	E C I	0 1 2 3	P D T N
To the Infrastructure (e.g., material delivery may snarl traffic)	yes no		0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3	E C I	0 1 2 3	P D T N
From the Environment (e.g., bad weather can disrupt concrete placement)	yes no		0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3	E C I	0 1 2 3	P D T N
From Adjacent Sites (e.g., structures in close proximity may restrict crane reach)	yes no		0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3	E C I	0 1 2 3	P D T N
From the Infrastructure (e.g., current infrastructure may not be able to support temporary water and energy needs)			0 1 2 3	0 1 2 3	0 1 2 3	0 1 2 3	E C I	0 1 2 3	P D T N

[a] 0 = not important; 1 = low importance; 2 = high importance; 3 = essential.
[b] E = expert knowledge; C = company data; I = industry data.
[c] 0 = unavailable; 1 = usually unavailable; 2 = usually available; 3 = always available.
[d] P = photo or picture; D = drawing or sketch; T = textual description; N = numeric.
[e] The information in this section draws heavily on Tatum (1988).

FIG. 4. Factors Affecting Constructability

analyzed to determine if modification to the CIM could incorporate them. According to an industry expert, this knowledge is very frequently considered in conjunction with constructability.

Fourth, rules or fundamental principles for untried concepts should be studied and considered for inclusion in the CIM. Such rules would provide assistance when no knowledge is available on a specific constructability concept. For example, an undocumented new technology or an existing technology applied to a new situation.

CONCLUSION

This research attempted to organize the knowledge considered during constructability assessment. The CIM proved to be useful under limited testing but requires further refinement and testing before it can be considered complete. Further, the developed classification system for retrieving the information was found to be useful but requires modifications for optimal efficiency. This research concludes that with additional refinement, the model presented can be used to capture, store, and retrieve constructability knowledge in an organized manner.

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APPENDIX I. SAMPLE ATTRIBUTE SURVEY QUESTIONS

In the first column of Fig. 4, factors are listed that describe issues possibly affected when optimizing a design for constructability. Examples and descriptions of the factors are provided appropriately.

For all factors ask yourself the question: did the constructability improvement require *changes* to this factor? The answer will be yes or no as shown in column 2 of Fig. 4. If the answer is no, skip to the next factor, else, complete the other questions.

In the third column of Fig. 4 comment in a word or two on the change that took place. For example, state "less tools" if the change for tool resources decreased.

Importance

Next in Fig. 4, four subcolumns are provided under the heading "importance." The subcolumns "system" and "component" refer to the impacted items filled in as part of the previous survey. For each impacted item, decide whether the factor affected the "method" and/or "sequence." Then ask the following question: how important was this factor's change to achieving the resulting improvement? Then, rate this importance with the following scale: 0 = not important; 1 = low importance; 2 = high importance; and 3 = essential.

Source

In the next column list the sources that the information is likely to have. Ask the question: where would information on the factor's change come from? Indicate the sources from these possibilities: E = expert knowledge; C = company data; and I = industry data. Expert knowledge refers to information only in someone's head. Company data refers to information written down in company files or databases. Industry data refers to information available from manufacturers or vendors.

Availability

In the next column please rate the typical availability of information from this source. Ask the question: how available is information from this source, on the factor's change? Rate this availability with the following scale: 0 = unavailable; 1 = usually unavailable; 2 = usually available; and 3 = always available.

Format

In the final column list the format that the information is likely to have. Ask the question: if you had to store information about this factor's change, what format would it be in? Indicate the format from these possibilities: P = photo or picture; D = drawing or sketch; T = textual description; and N = numeric.

APPENDIX II. REFERENCES

Blair, D. C., and Maron, M. E. (1985). "An evaluation of retrieval effectiveness for a full-text document retrieval system." *Communications ACM*, 28(3), 289–299.

Boeke, E. H., Jr. (1990). "Design for constructability: a contractor's view." *Concr. Constr.*, 35(2), 198–202.

Burkhardt, A. (1987). "Repeating formwork greatly reduces costs." *Concr. Constr.*, 32(10), 853–855.

"Constructability: a primer." (1986). *Publication 3-1*, Construction Industry Institute, University of Texas at Austin, Texas.

Fischer, M. (1991). "Using construction knowledge during preliminary design of reinforced concrete structures," PhD thesis, Stanford University, Stanford, Calif.

"Guidelines for implementing a constructability program." (1987). *Publication 3-2*, Construction Industry Institute, University of Texas at Austin, Texas.

Hanlon, E. J. (1993). "Classifying constructability information." *Tech. Rep. No. 29*, Computer Integrated Construction Research Program, The Pennsylvania State University, University Park, Pa.

Hanna, A. S. (1989). "An interactive knowledge based formwork selection system for buildings." *Tech. Rep. No. 11*, Computer Integrated Construction Research Program, The Pennsylvania State University, University Park, Pa.

Ioannou, P. G., and Liu, L. Y. (1993). "Advanced construction technology system—ACTS." *J. Constr. Engrg. and Mgmt.*, ASCE, 119(2), 288–306.

Khayyal, S. A., and Sanvido, V. E. (1990). "Towards a master builder information framework for project developers." *1990 Annu. Conf.*, Canadian Society for Civil Engineering, Hamilton, Ontario.

"More construction for the money." (1983). *In-house publication*, Business Roundtable, New York, N.Y.

O'Connor, J. T., Rusch, S. E., and Schultz, M. J. (1987). "Constructability concepts for engineering and procurement." *J. Constr. Engrg. and Mgmt.*, ASCE, 113(2), 235–248.

Paulson, B. C., Jr. (1976). "Designing to reduce construction costs." *J. Constr. Engrg. and Mgmt.*, ASCE, 102(4), 587–592.

Sanvido, V. E. (1990). "Towards a process based information architecture for construction." *Civil engineering systems*, London, U.K., 7(3), 157–169.

Sanvido, V. E., Khayyal, S., Guvenis, M., Norton, K., Hetrick, M., Al Muallem, M., Chung, E., Medeiros, D., Kumara, S., and Ham, I. (1990). "An integrated building process model." *Tech. Rep. No. 1*, Computer Integrated Construction Research Program, The Pennsylvania State University, University Park, Pa.

Smith, C. C. (1993). *Professional interview*, Beacon Construction Co., Boston, Mass.

Tatum, C. B. (1987). "The project manager's role in integrating design and construction." *Project Mgmt. J.*, 18(2), 96–107.

Tatum, C. B. (1988). "Classification system for construction technology." *J. Constr. Engrg. and Mgmt.*, 114(3), 344–363.

Tatum, C. B., Vanegas, J. A., and Williams, J. M. (1986). "Constructability improvement using prefabrication, preassembly, and modularization." *Tech. Rep. No. 297*, The Construction Institute, Department of Civil Engineering, Stanford Univ., Stanford, Calif.

Touran, A. (1988). "Concrete formwork: constructability and difficulties." *Civ. Engrg. Practice*, 3(2), 81–88.

J. Constr. Eng. Manage., 1995, 121(4): 337-345