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SUPPORTING AUTOMATED CONSTRUCTABILITY CHECKING FOR FORMWORK CONSTRUCTION: AN ONTOLOGY

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GUEST EDITOR: Dimyadi J. & Solihin W.

Li Jiang, Ph.D., VDC Coordinator
Austin Commercial, L.P.
ljiang@austin-ind.com

Robert M. Leicht, Ph.D., Associate Professor
Department of Architectural Engineering, The Pennsylvania State University
rmleicht@engr.psu.edu

SUMMARY*: Constructability review has been an ongoing area of research to support integrated design and construction processes for decades. As the evolution of Building Information-modeling (BIM) shows great potential to motivate integrated design and delivery, the current manual review process, which is time-consuming and error-prone, is facing a transformation with the adoption of advanced technology in a more collaborative environment. Focusing on reinforced concrete structural elements, the current work developed an ontology of constructability review to support automated constructability review through the employment of BIM. Underlying interdependencies between design and construction were identified, along with the associated information requirements to pursue the automated constructability reasoning. The constructability relationships with associated information requirements and its applicability, were validated through a series of expert interviews and a case study. The established constructability ontology underpins the understanding of the constructability concepts for the benefits of integration, and the implementation of these concepts with proactive construction-specific design feedback. Unlike the fragmentation of traditional project delivery, the encouragement of construction input at early design stages has been found to promote close collaboration among different project participants with consistent commitments, leading to integrated design and construction.*

KEYWORDS*: constructability, BIM, ontology, constructability review, automated checking, constructability relationships, integrated design*

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1. INTRODUCTION

A new building project requires people in different professions across architecture, engineering, and construction to work together on a product for the client. The design of the product needs to incorporate the requirements in different disciplines, such as codes and standards for the building structure. To enhance the building performance, additional requirements like sustainable design or maintenance requirements, are sometimes considered. Unlike well-documented design codes and standards, the construction-specific requirements largely come from the individual experts' knowledge and experience. Due to the fragmented design and construction processes, obtaining and handling the construction-specific information takes extensive time (Baya & Leifer, 1996), which impedes the implementation of the concepts to ease construction. The Construction Industry Institute (CII) defines these concepts as "constructability" (CII, 1986).

To have an effective and efficient constructability implementation, the timing of constructability feedback is critical; because late construction input will be likely to lose its value and cause more change orders or rework, as the design progresses (CII, 1986; O'Connor and Miller 1994). With a checklist of constructability concepts organized by construction professionals in an organization, the traditional practice of a constructability review is to manually review design documents at certain design milestones, such as 30%, 60%, or 90% design completion. The amount of rework caused by the retrospective review of design decisions that have been already made, along with the extensive consumption of time and manpower due to the manual practice, greatly undermines the value of constructability input. The review of current constructability tools (Jiang et al., 2013) indicated the application timing are mostly in late design development phase; thus, raising the question of how to integrate constructability feedback at earlier design stages to improve the construction process.

Like manufacturing, the wave of computing product information encourages ideas of automation in the Architectural, Engineering, and Construction (AEC) industry, to improve process efficiency. An automated constructability review was proposed to simulate the constructability reasoning in construction experts' minds, by representing the constructability knowledge with associated building information (Jiang and Leicht, 2014). Automated checking is envisioned to systematically examine construction-specific design information through project design and help generate constructible design decisions.

To support automated constructability review, it is critical to fully understand the constructability concepts and the relationships between design information and construction means and methods. An ontological approach was therefore needed, to provide explicit formal, machine-interpretable specifications of the concepts and relationships in the domain of constructability. Ontologies have been developed, represented with appropriate modeling, and adopted in a variety of domains for communication and knowledge sharing, logic inference and reasoning, and knowledge reuse (Zhang, 2014). This paper introduces the ontology of a constructability review through modeling the design- and construction- related concepts, interrelationships between the concepts, and axioms. To narrow down the scope of the research, formwork construction of Cast In Place (CIP) concrete structures became the focus, considering the power of control in shaping CIP concrete structures from designers and builders and the cost impact of formwork construction. An ontology-based approach is then developed to capture and define the interdependencies between the construction and design information. Through the ontology, the constructability relationships can be prototyped with available model content for automated checking, demonstrating the potential transformation of the currently manual constructability review process into an automated and proactive approach. Experts' interviews were applied to validate the informational relationships within the ontology. Using the identified constructability relations between design and construction information to support an automated, constructability review is discussed and concludes the paper. The next section starts with the review of constructability concepts and related ontology research.

2. BACKGROUND

The nature of a building project suggests the interdependencies between design and construction. Fischer and Tatum (1989) organized the concepts into two major groups: factors exogenous to the design, which describe the factors beyond the control of designers; and factors indigenous to the design, e.g., modularity and repetition, which designers can directly influence through design decisions to enhance constructability. Fischer and Tatum (1997) further classified the indigenous factors associated with different levels of detail of design content, from vertical and horizontal layout, to dimensions of design components, and then to detailed design. Similarly, viewing constructability factors as either input to design process or impacts on design product, Lam et al. (2006) investigated 20 attributes of constructability and highlighted 5 major areas of potential contributions of designers for constructability: site conditions, coordination between documents/components/working sequences, standardization and repetition, safety, and ease of construction. With the efforts on understanding the impact of constructability concepts on design decisions, the links between the product design features and construction constraints are still limited to help build a systematic approach to integrate constructability requirements into design thinking.

The AEC industry is not the only industry that seeks to integrate product design with the production process. In fact, the manufacturing industry has been practicing design for manufacturability to obtain the desired quality and production rates while optimizing cost (Shankar & Jansson, 1993). Shankar (1993) investigated manufacturability concepts and applied quantitative metrics to help designers evaluate the manufacturability of a product design while making design decisions. The analysis of the process identifies the tasks that affect the manufacturing process; then the analysis of the product allows the designers/engineers to link the manufacturability impacts with the associated design features and product variables. As shown in Figure 1, five groups of manufacturability concepts were defined with sub-categories of factors that designers can influence with different decisions (Shankar, 1993).

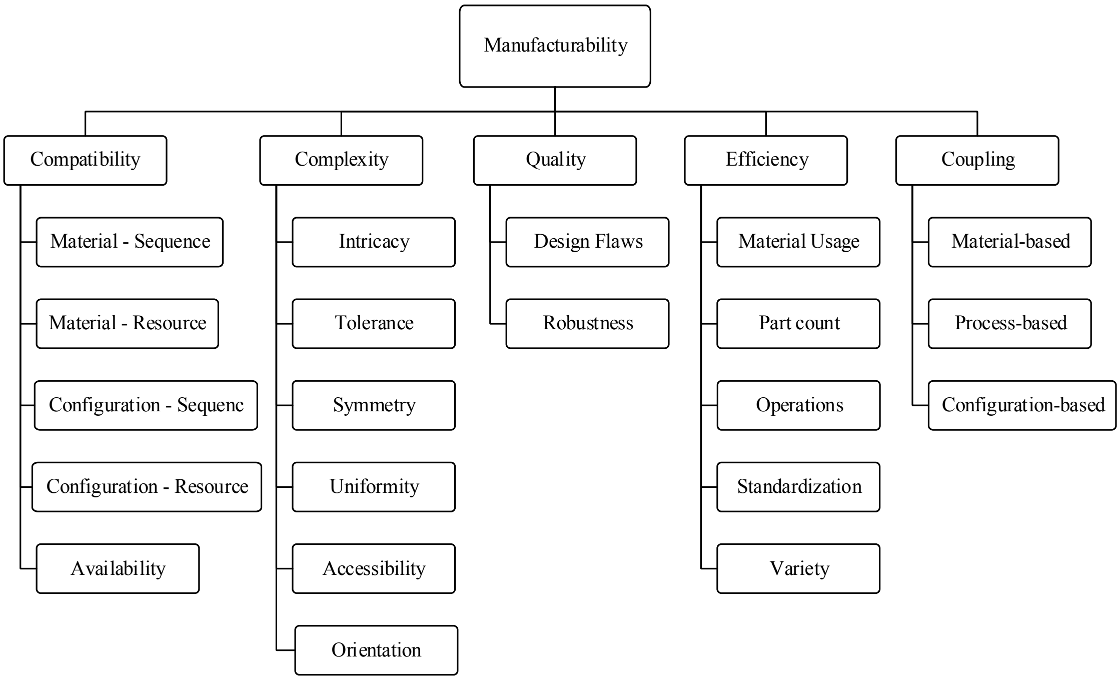

FIG. 1: A hierarchical model of manufacturability concepts (adapted from Shankar, 1993)

To better analyze and present the links, an object-oriented information model was applied to represent the production constraints, as well as the relationships between design parameters and their impact on production (Giachetti and Alvi, 2001). The model then built the foundation of a manufacturability review system to aid design engineers in performing evaluations. The so-called "manufacturability review system" (Giachetti and Alvi, 2001) is essentially an expert system, which relies on a set of manufacturability rules to precede automated manufacturability analysis. This approach for manufacturability review and evaluation was widely recognized to be more consistent, reliable, and efficient in identifying potential manufacturing issues and responding with feasible design alternatives (Gupta and Nau 1995, Molcho et al. 2008, Nagahanumaiah and Ravi 2008). The involvement of computer-aided technology was an integral resource in the process that promoted the integration of design and manufacturing (Prasad 1996, Dong 1996)

Likewise, the benefits of applying innovative information technology in design and construction processes have been recognized in terms of efficiency through reduced rework, effectiveness by increasing the ability to exchange data and improved quality of output, and performance resulting from improved integration (Andresen et al., 2000). With the emergence of Building Information Modeling (BIM), project stakeholders have better opportunities to share their knowledge and exchange the information to support their services through collaboration. Automating the compliance checking of a project design has been researched in a variety of areas, including building envelope (Tan, et al., 2010), structural design (Nawari, 2012), fire code compliance (Dimyadi, et al., 2014), safety requirements (Zhang, 2014), and environment regulatory compliance (Zhou & El-Gohary, 2015). Regardless, few studies have explored the opportunity of leveraging BIM to transform the constructability review process, even though it was considered to have visual, informational, automational, and transformational benefits (Fox and Hietanen 2007, Jiang, et al. 2013). An automated, rule-based constructability checking was proposed and tested for formwork construction through a pilot study (Jiang and Leicht, 2014). As the first and the foremost step (Figure 2), constructability knowledge needs to be elicited and formalized to reveal the relationships between design and construction information that can be written into machine-readable constructability rules. Jiang et al. (2014) introduced mixed-methods elicitation to collect constructability knowledge from construction professionals.

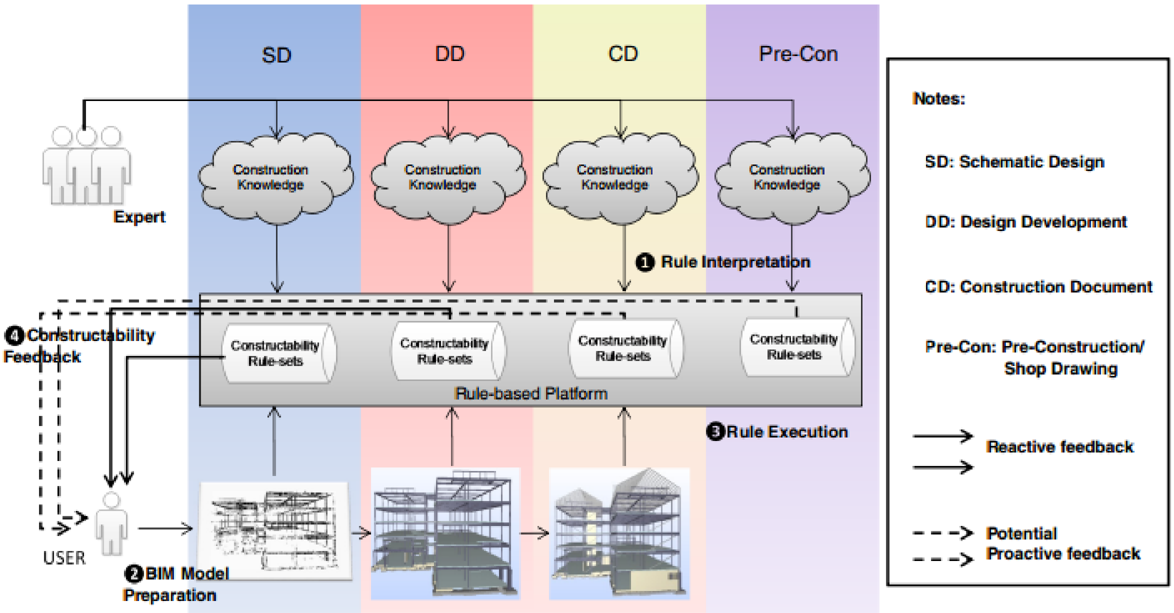

FIG. 2: Rule-based constructability checking (Jiang and Leicht, 2014)

Building on earlier efforts, the current work focuses on the formalization of the constructability knowledge with an ontology-based approach to enable the automated checking. Ontology was interpreted as a shared conceptualization (Borst, 1997), where "the ontology should be machine-readable" (Studer, et al., 1998), and shared refers to our knowledge within a domain and thus can be represented and reused for applications such as knowledge-based problem solving (Chandrasekaran, et al., 1999). In the construction industry, ontologies have been used to help researchers encode construction-specific knowledge with design properties and parameter values to solve integrated problems (Nepal, et al., 2012). Ugwu et al. (2004) developed an ontology for agent-based collaborative design and decision-making of portal frame structures, through the identification of the relationship between product variables and constructability, safety, energy efficiency, or cost. Staub-French and Nepal (2007) developed an ontology of component features and similarity, to develop a generic reasoning process of investigating the impacts of design conditions (e.g., component similarity) on construction cost performance. Kim and Fischer (Kim & Fischer, 2007) investigated a formalized representation of product component features and action features to automate the temporary structure selection process, and pointed out "information technology-based methods are the most promising approach to improve the timeliness, correctness, and consistency of the temporary structure planning process." Zhang (2014) focused upon construction safety and applied an ontology-based approach to formalize safety management knowledge and achieve an automated safety planning for job hazard analysis. The relations between product design, construction process, and construction safety were investigated through modeling the three domains (Zhang, 2014). Likewise, the ontology of a constructability review, which will be described in the next section, is expected to formalize constructability knowledge through the relations between design, construction, and constructability concepts, to support early constructability feedback through an automated constructability review.

3. THE ONTOLOGY OF CONSTRUCTABILITY REVIEW

The ontology of a constructability review knowledge is illustrated in Figure 3, based on the constructability review captured through the mixed-methods elicitation (Jiang et al., 2014). Three domains and their interrelationships were modeled with the representation of the main concepts that are involved in a constructability review: product (blue block), production (yellow block), and constructability (purple block). TABLE 1 provides the definition of each concept shown in FIG. *3*.

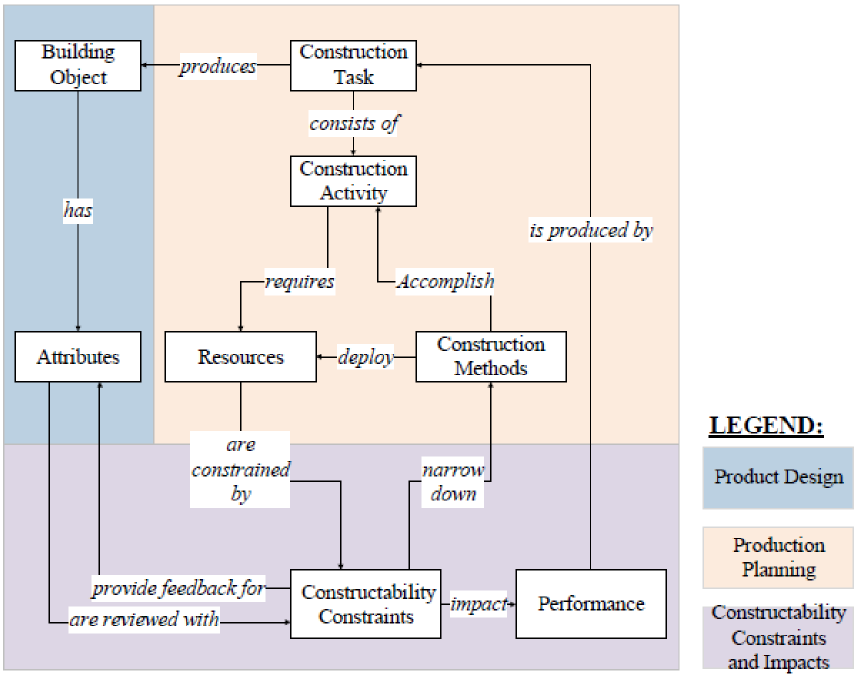

FIG. 3: An object-oriented representation of the ontology of a constructability review

TABLE 1: Domain concepts involved in a constructability review

Domain	Class/Concepts	Definition	Examples
Product	Building Object	a distinguishable physical part of a building (Ahn, et al., 2010), including individual component object or an assembly of components as system object.	a floor slab, a door, or wall
	Attribute	a feature or property regarded as a characteristic or inherent part of an object (Dictionary, 2013).	thickness of a concrete slab
Production	Construction Task	an operation performed by an individual, crew(s), and/or equipment, producing a measurable deliverable or building object (Zhang, 2014).	slab construction
	Construction Activity	the subdivision of construction tasks, referring to the work associated with scheduling function. It focuses on an action taken that contributes to a construction task but does not directly produce a building object (Halpin et al. 1987, Zhang 2014).	place rebar, or pour concrete
	Construction Method	the means used to transform resources into constructed products (Tatum, 1988).	pumping concrete
	Resources	the essential inputs to construction method to achieve a desired construction product (Tatum, 1988).	material, equipment
	Performance	the results of accomplishing a construction activity or task (Hanlon and Sanvido, 1995).	cost, quality

Construct-ability	Constructability Constraints	the factors that exogenously or indigenously impact design decisions to enhance constructability (Fischer and Tatum, 1989).	accessibility

In a typical constructability review, a product design, which consists of a variety of building objects and attributes to achieve the functionality, is reviewed to identify constructability constraints that would impact the performance of a construction tasks. The constructability constraints are identified by human experts, such as experienced project engineers or superintendents, indicating resources that are required for associated construction activities and the available construction methods to build the product (FIG. *3*). Through the review, the constructability constraints can help construction professionals narrow construction options and determine the best construction method for the project; on the other hand, the comments also serve as the feedback for product design to make more constructible design decisions (Jiang, et al., 2015). The design attributes, therefore, serve as variables that are linked with construction considerations to impact the production performance.

Based on the representation of the domain concepts and the relationships, the product and production information can be organized and aligned to identify the constructability constraints and corresponding design attributes. More importantly, the mapping of the concepts provides an approach to query the constructability constraints or relationships across the product and production domain, which establishes the informational basis of an automated constructability review to facilitate input for a product design. Starting by introducing the three domain information models in more detail, the following sections then present the ontology-based approach to define the constructability relationships between the product and production information, and structure the information requirements for an automated constructability checking based upon the defined relationships.

3.1 Product Information Model – Product Information Architecture

To investigate the required design information for a constructability review, a product model is needed to decompose the product design from high-level classes to detailed product information. A top-down hierarchical approach of information architecture, which is based on class, design attribute, and information decompositions, was chosen to organize the product information, considering the straightforward and user-friendly nature of the approach (Rosenfeld & Morville, 2002). Focusing on structural information, Solnosky and Hill (2013) provides a classification of structural systems and their components that supports the modeling approach for structural design. It was developed as part of the Integrated Structural Process Model (ISPM), which is a collaborative and integrated approach through information models by providing critical decision tasks and information exchanges at each design stage (Solnosky, 2013). With the classification, a cast-in-place (CIP) concrete structure (FIG. *4*) was used in this research as an example to investigate the hierarchical aggregation of the structural design information and the relationship between design and construction information. The hierarchical classification was also organized by different levels of detail of building information that can be mapped by design stages (Pulaski & Horman, 2005), indicating the design decision point that can incorporate or provide construction-specific feedback to improve the constructability.

As illustrated in FIG. 4, the top-down decomposition demonstrates different levels of detail for classes and associated design attributes as the design evolves, from system level class at the top, to sub-system, to component and elements at the bottom. Both permanent systems and temporary systems can be included, though temporary structures such as concrete formwork are not shown in detail in the example. Permanent systems are defined as the systems that remain in situ for the life of a building, for example, a building's facade. On the contrary, temporary structures are those built in place solely to enable the construction of the final product, such as scaffolding or formwork systems.

FIG. 4 focuses on permanent structural systems and dissects it into two dominant classes: sub-structure and super-structure. The system level of design information is defined, such as load assumptions and available material. Then, each system is decomposed into sub-systems, foundation, lateral, and gravity systems specifically. Further dissecting sub-systems, component and element levels of classes and design information are defined. Using gravity systems, more specifically floor system as an example, components like slab and beam, and elements, such as connections, are considered and defined with associated attributes. More detailed attributes, like sections and reinforcing details, are usually designed with associated values at the detailed design stage.

Depending on the progression of design information, the decision regarding temporary systems can be narrowed down by contractors to develop the construction plan that best meets schedule and budget. Accordingly, the product information of temporary systems can similarly be decomposed in system, sub-system, component, and element level of classes. The decomposition is a necessary first step for constructability, to understand the interdependencies between the design decisions, regardless of whether they are permanent or temporary systems. For production principles need to be considered, the links need to be able to be defined at more detailed levels of systems, components, and material information, requiring this type of architecture.

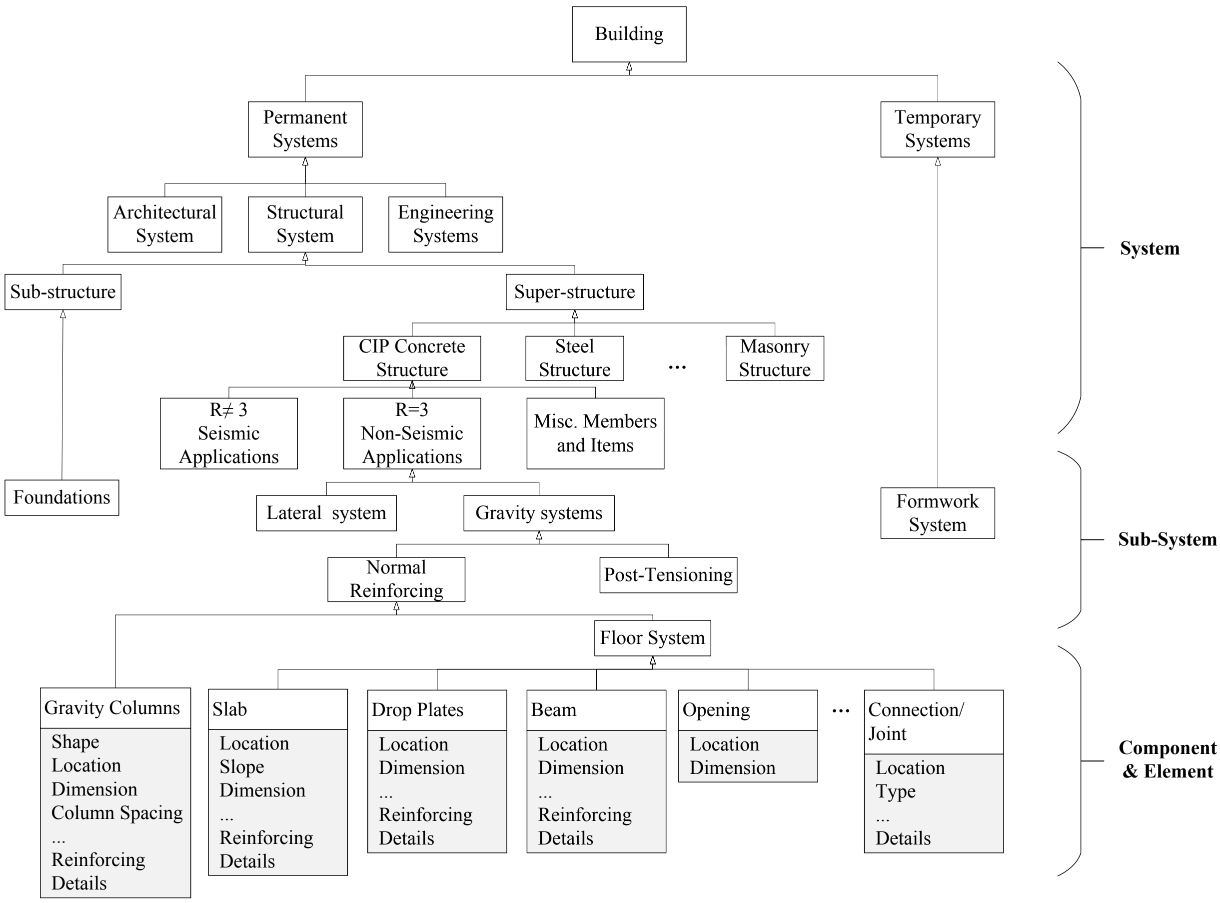

FIG. 4: Example product information architecture of Building A with Cast-In-Place Concrete Structure

3.2 Production Information Model – Work Breakdown Structure (WBS)

Similar to the product information definition, the production process was broken down into tasks and activities for production planning to investigate constructability constraints. An approach of breaking down the construction process into detailed levels for project control, Work Breakdown Structure (WBS), was applied to define the flow of information between design and construction. FIG. **5** shows an example WBS of new construction building project designed with CIP concrete structure.

Based on a typical WBS breakdown (Halpin, et al., 1987), Level 00 represents the project, which can be divided into several major areas for control and management. Those areas are defined as Level 01 of the breakdown structure. Then, each control area is broken down by disciplines, such as architectural and structural. For example, the Process Area 02 is a new construction area that has all disciplines from earthwork to mechanical, electrical, and plumbing (MEP) construction. Each discipline of construction work is further broken down into tasks, from system, Level 03, through component, Level 05. Depending on the construction type, each task can be further divided into a series of activities at Level 06 and sub-activities in Level 07, that are associated with the scheduling function and refer to the work represented in a schedule diagram, such as a Gantt chart (Halpin, et al., 1987). For a CIP concrete structure, the task of constructing a slab contains three typical groups of construction activities: formwork assembly, rebar installation, and concrete placement. Formwork activities were broken down into fabricating, erecting, and stripping with resource requirements of each sub-activity to plan the production process (Hurd, 2005). According to Tatum (1988) and Hanlon and Sanvido (1995), nine resource requirements are defined as the essential input of the CIP formwork production process: information, general conditions, equipment, material, space, skills, tools, energy, and time. Added to the original WBS, the nine resources become the more detailed level of production information for project control in this research. The detailed breakdown of the construction process with resource requirements enables project teams to identify construction constraints for each activity and then plan the appropriate method to build the project. In addition, the information breakdown for the construction means and methods support of specific tasks are defined at a level that the links to the design model characteristics could be extracted and analyzed for constructability.

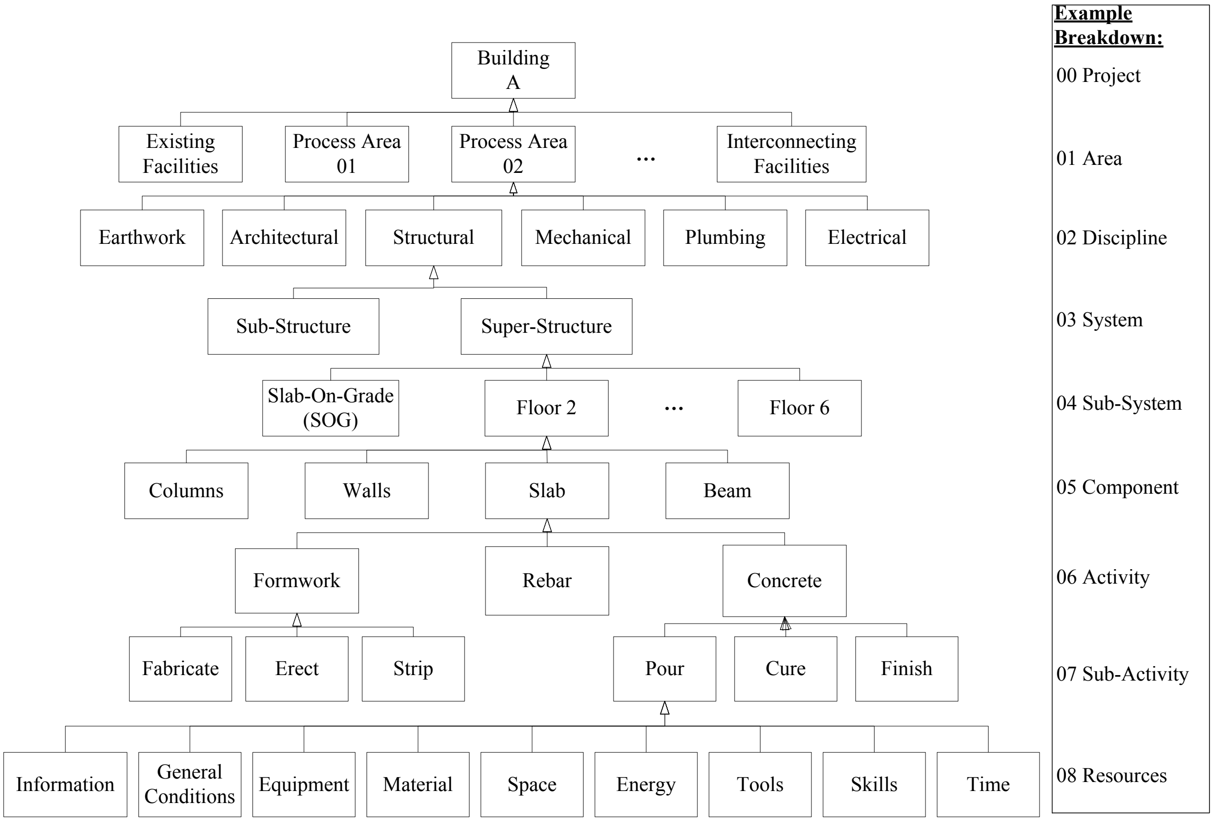

FIG. 5: Example WBS of a building project

3.3 Construction Information Model – A Hierarchy Model of Constructability Constraints

Based on the earlier classifications in the field of manufacturing (Shankar 1993, Rais-Rohani 1996, Curran, et al., 2002), a hierarchy model of constructability constraints was developed (FIG. ***6***). Three major categories of constructability constraints were defined: compatibility-related, complexity- and efficiency-related, and coupling-related constraints. It should be noted that the factor of "Orientation" was greyed out because no related constructability considerations regarding formwork construction were captured in this research. However, "Orientation" can be a constructability constraint in other type of building structure or other building systems. One example could be the consideration of the column orientation to minimize the number of skewed connections of a steel-framed building and then the complexity of construction tasks (Schumacher, 2002). Thus, with the focus of CIP concrete structure, the following three sections will discuss each category and sub-categories in detail with corresponding examples; the factor of "Orientation" will not be included in the discussion.

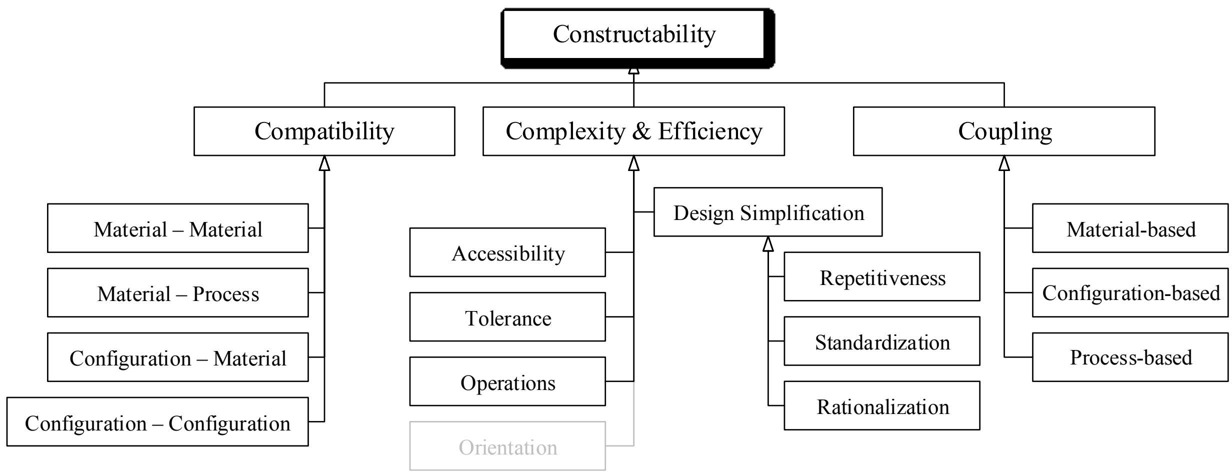

FIG. 6: A hierarchy model of constructability constraints

3.3.1 Compatibility-related Constraints

Compatibility-related constraints describe the compatibility between a product design and production process. Based on Shankar & Jansson (1993) and the decomposition of building design information, a product design specifies building material and configuration; whereas the analysis of a production process consists of a sequence of activities, and the variety of resources that are required for a specific construction method to accomplish an activity. Any conflicts between design components and process requirements will cause compatibility challenges. Thus, four sub-categories of compatibility-related constraints are: (1) material – sequence, (2) material – resource, (3) configuration – sequence, and (4) configuration – resource. TABLE 2 provides a list of the constraints and descriptions, along with examples for further illustration of each relationship.

TABLE 2: Compatibility-related constructability constraints and examples

Compatibility-related Constraints	Description	Constructability Example
Material – Sequence	Describes the compatibility of a material system with the interdependencies between construction activities.	A building structure of CIP concrete has different workflows for construction than that of steel erection.
Material – Resource	Describes the compatibility of a material system with the resource requirements of a specific construction method.	A high-rise building designed with high performance concrete (e.g., 10 000 psi or higher) constrains the resources (e.g., concrete availability, skilled labor) to perform the work.
Configuration – Sequence	Describes the compatibility of design configuration with the interdependencies between construction activities.	Increasing the load capacity of floor would reduce the level of reshoring, which can impact the construction sequence in terms of shoring and re-shoring.
Configuration – Resource	Describes the compatibility of design configuration with the resource requirements of a specific construction method.	Applying tower crane with the internal climbing method requires structural configuration to ensure its feasibility.

3.3.2 Complexity- and Efficiency- related Constraints

The second classification of constructability constraints focus on complexity- and efficiency- related relationships. These constraints indicate the impacts of product design on the complexity and the efficiency of the production process.

- Baccarini (1996) defined the complexity of a construction project as, "consisting of many varied interrelated parts and can be operationalized in terms of differentiation and interdependency." For a production process, the complexity by differentiation refers to the diversity of certain aspects of a task, such as the number of inputs and/or outputs, number of separate and different tasks necessary to produce the end-product, or the number of different trades involved on a project that may require coordination. The production complexity by interdependency includes the interdependencies between tasks, teams, methods, and different inputs (Baccarini, 1996).
- Efficiency refers to production process efficiency. It can be measured by the minimum use of resources applied in production (Ulrich & Eppinger, 2011), for example, the maximum reuse of forms, or the minimum set-up and handling time.

Thus, the constraints that can have impacts on production complexity and efficiency are identified as: (1) repetitiveness; (2) standardization; (3) rationalization; (4) accessibility; (5) tolerance; and (6) operation (FIG. ***6***). Description and corresponding example of each constraint are provided in TABLE 3.

TABLE 3: Complexity- and efficiency- related constructability constraints and examples

Complexity and Efficiency-related Constraints	Description	Constructability Example
Repetitiveness	Describes the repetition of the features of building objects, such as bay layout, dimension, and other design requirements (Jarkas, 2015).	The connections between beams and columns that occur in dozens of instances within each floor are designed exactly the same to ease the learning curve
Standardization	Describes that the design or configuration of building objects are fixed with respect to accepted dimensions, criteria, materials, or parts (Fischer & Tatum, 1989).	Columns are slightly oversized to increments in line with standard lumber sizes or fixed formwork dimensions.
Rationalization	Describes "the minimization of the number of materials, sizes, components, or sub-assemblies (Moore, 1996)."	The arrangements of floor perimeters are rationalized to avoid extensive activities (e.g., setting out, planning, and measurements), resulting in a significant saving in labor productivity (Jarkas, 2015).
Accessibility	Describes the impacts on the space or logistical paths required for material or personnel to appropriately reach and install material at the work face (Hanlon & Sanvido, 1995).	The faces of beams can be 2 inches wider than the faces of the column to minimize rebar interference, providing the access for proper concrete consolidation (Richardson, 1983).
Tolerance	Permissible variation or deviation from a specified value, such as surface, deflections, location, or dimension of building objects (ACI, 2006).	Facade anchors can be designed or specified with adjustment in the anchor point to the structure to allow for a minimal amount of deviation for the embedded anchor from its designed elevation.
Operation	Describes the impacts of the required features of a building object on the number of construction tasks/activities including handling, or the set-up time (Shankar, 1993).	To avoid drop panel, a steel shear head can be used as the alternative for slab-column connections, reducing the activities and making construction work quicker.

3.3.3 Coupling Constraints

The third category of constructability constraints, coupling constraints, describes the relationships between the design decisions and the functional and production requirements of the product design. Although the term "coupling" has been used more often in the manufacturing world, similar examples of coupling relationships can be found in the AEC industry. Using the constructability example for "Operation" in TABLE 3, the decision of replacing the drop panel design with steel shear head for slab-column connections influences different aspects or parameters of design and construction. It adds more shear resistance to the slab and helps to reduce slab thickness, and in the meantime, eliminates the activities for building forms for drop panels, making the work quicker and more economical by taking advantage of flying forms. However, on one hand, using steel shear head typically requires 6-8 weeks lead time to acquire the steel stud rails and the density of reinforcing needs to be checked for congestion. According to Shankar (1993), the design feature or parameter that is involved in a coupling relationship is defined by the coupling variable (e.g., slab-column connection). As the example shows, the change of the coupling variable from using steel shear head instead of drop panel impacts the requirements of the design and construction in different and opposite ways. Thus, the knowledge of the coupling variable(s) and their impacts on the requirements are important from the early design stages for making more constructible design decisions. There are three categories of coupling constraints that may impacts constructability: (1) material-based coupling; (2) configuration-based coupling; and (3) process-based coupling. TABLE 4 provides the description and an associated example of each category.

TABLE 4: Coupling constraints and examples

Coupling Constraints	Description	Constructability Example
Material-based Coupling	Focuses on the coupling relationship between material parameter(s) and the requirements.	Self-consolidating concrete enables a faster placement rate and lower placement cost, but it would produce higher pressure on the forms and requires skilled labor for application.
Configuration-based Coupling	Focuses on the coupling relationship between design configuration and the coupled requirements.	Reducing the depth of horizontal structural components (e.g., slab and beam) can lessen the weight of the structure, the sizing of columns and foundation, and the overall cost of the structure. However, other factors such as vibration requirements and the contractor's skill level should be taken into consideration.
Process-based Coupling	Focuses on the coupling relationship between parameters of a production process and the requirements.	The process for placing an extremely thick concrete wall requires adjustments in the pour rate as well as potential cooling techniques to keep the concrete from cracking from excessive heat while maintaining the placement and structural integrity of one continuous pour.

3.4 Ontology-based Approach to Support Automated Constructability Checking

Using the three domain models, an ontology-based approach was developed and deployed to identify and map the underlying constructability links between the product design and production information. A conceptual representation of the approach is shown in FIG. 7.

Consistent with FIG. 6, FIG. 7 indicates the three developed domain information models in colored blocks: product model in blue, production model in yellow, and constructability information model in purple. Focusing on the use of CIP concrete structure, one example of constructability constraints is shown and linked with associated product and production information (FIG. 7).

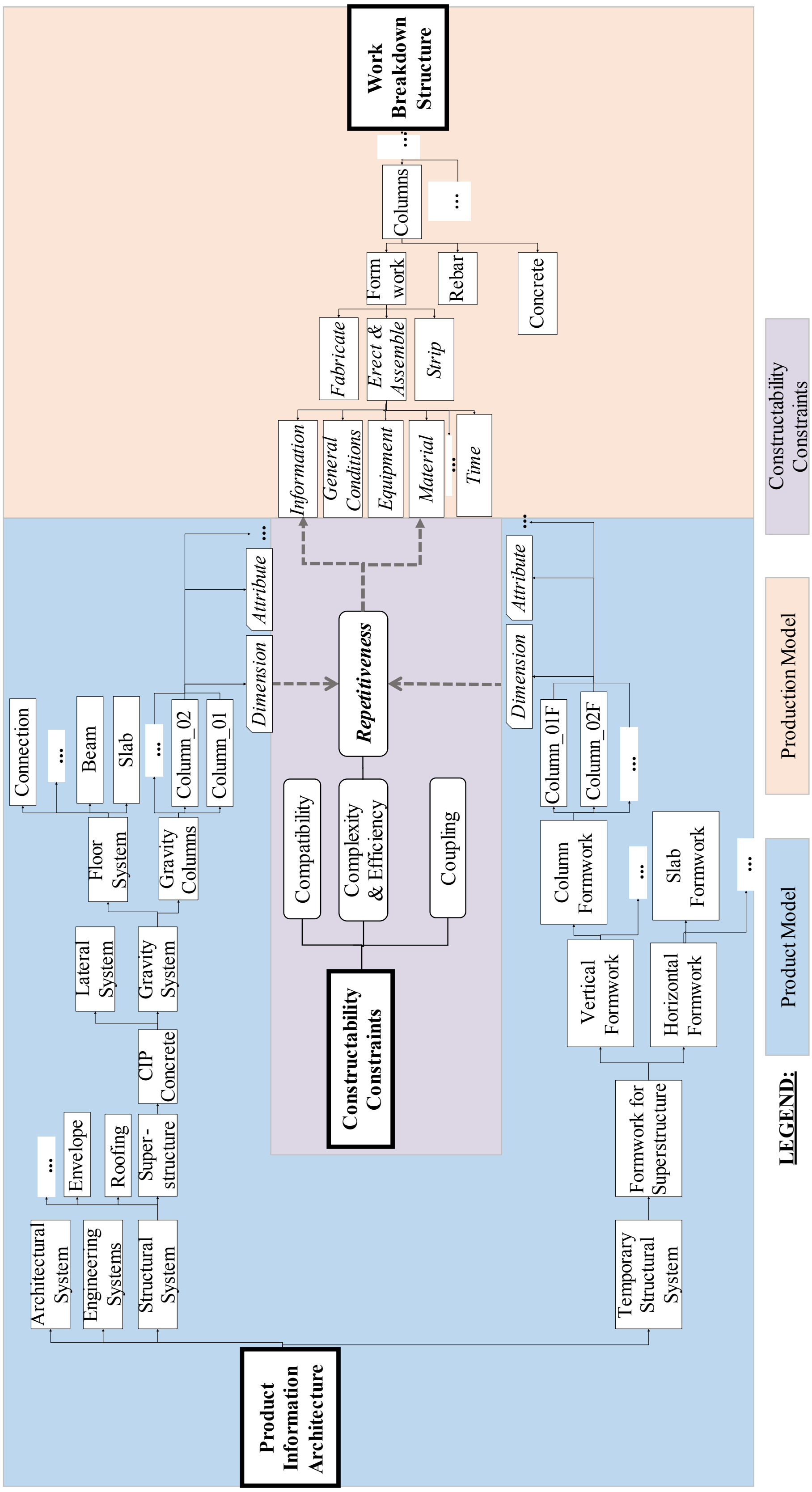

FIG. 7: An ontology-based approach to reveal constructability links between product and production information

- **Product model**: The hierarchy model of a CIP concrete structure is shown by the blue block (FIG. ***7***). Starting from the left, the building information architecture breaks a physical building product down into different systems (e.g., "Structural" and "Temporary" systems), components (e.g., "Column_01"), and elements (e.g., "Connection"), with associated design attributes (e.g., "Column_01" – "Dimension").
- **Production model:** The yellow block (FIG. ***7***), indicates the construction work of the given CIP concrete structure was broken down to align the building objects (e.g., Column) and attributes (e.g., Column – Dimension) with associated construction tasks (e.g., Column as a task in WBS) and activities (e.g., Formwork, Rebar, and Concrete for column construction), in order to reveal the independencies between design and construction.
- **Constructability constraints:** Constructability constraints are identified at the intersection points within the purple block in FIG. ***7***. Different interactions of product and production-related information indicate different constructability relationships, allowing constructability constraints to be analyzed. In return, the investigation of constructability constraints provides links to sort out design variables that can be aligned with construction decisions. In this example (FIG. ***7***), given that all the building columns are designed as square CIP columns in the same 24"x24" dimensions, the uniformity of the cross-section dimension determines the size of form panels, indicating that they can be used repetitively to perform the work. The repetitive work flows of column production reduce the complexity of the construction and promotes efficiency of the process, maximizes reuse of forms, reduces learning curve, and minimizes diversity of operations (Burkhart et al. 1987, Touran 1988). To reveal the interdependencies, as shown in FIG. ***7***, the constructability constraints are linked with both associated design attributes (i.e., "Dimension") of permanent and temporary systems and resource requirements of construction activities. By capturing the design value of the attributes, computational reasoning can be applied to analyze how production can be affected by uniform design configurations. With the results, the project team can determine the approach for production based on the identified impacts on production-applied resources.

Therefore, with the ontology-based approach, the constructability relationships between the design and construction information were captured through the identification of the constructability constraints and the linking design information and WBS details. The associated design attributes captured in different levels of details for each constructability relationship were used to map the potential timing of constructability feedback based on corresponding constraint(s) (FIG. ***8***). Taking the first constructability constraint (i.e., "Material-Resources" in Figure 8) as an example, one example obtained from experts and is the use of high performance concrete (10,000 PSI or greater) in a high-rise building design. The design information is the strength property of the material (i.e., concrete for structural system); as a result, the resource-related constructability shown in Figure 8 can be obtained at the system level of design. As illustrated, constraints that can be reviewed at very early design stages with building level and system/sub-system level of design information are: Material – Resource, Configuration – Resource, Configuration – Sequence, Design Simplification, Accessibility, Operations, and coupling constraints (i.e., Material-based, Configuration-based, and Process-based). The analysis of other constraints may require more detailed information about building components, or even elements, to provide related constructability feedback. FIG. ***8*** also suggests the design-related constructability feedback that can be linked with related resource requirements for construction process. In the example of Material-Resource constraint, the Material and Skill requirements were considered related resource requirements for construction and linked with the constraint in Figure 8. Regardless of constraints, more feedback can be provided regarding Information, Material, and Time requirements through automated checking the associated design attributes. On the contrary, it is difficult to align design attributes with Energy requirements, because the amount and the type of energy used in construction are largely influenced by exogenous factors, such as weather, that are beyond designers' control. By following the interactions back to associated design information, the information requirements for an automated constructability review can be defined to represent different constructability constraints and address construction means and methods considerations or resource requirements.

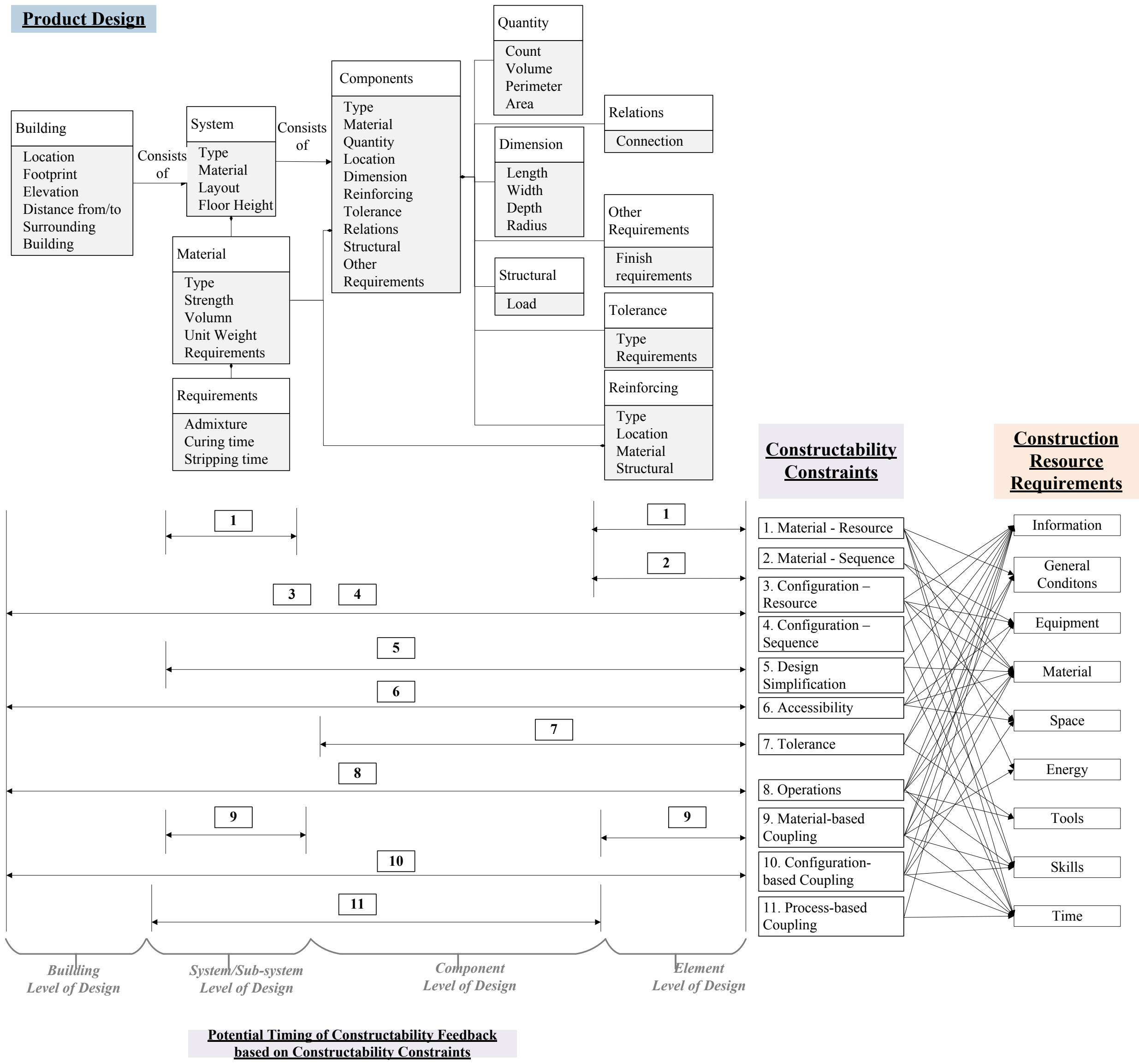

FIG. 8: Summary of constructability relationships

3.5 Information Requirements for an Automated Constructability Checking

With the use of the ontology-based approach, the information and interdependencies are defined to provide the essential elements for computer-aided reasoning to perform automated constructability analysis. The structural elements of a CIP building super-structure became the focus, primarily including slab, beams and girders, gravity columns, and load-bearing walls. Foundation elements were ignored from the study objects due to the heavy involvement of exogenous constraints, notably site conditions.

Based on the information structure of a design adopted in the ontology-based approach (FIG. 8), the variables for checking the compatibility-related, complexity- and efficiency- related, and coupling impacts on production process are summarized: *Building*, *Material*, *Structural*, *Location*, *Dimension*, *Quantity, Relations, Tolerance* and *Other Requirements*. The level of detail of the related design information (e.g., *System Material* or *Component Material*) indicate the potential timing of the constructability feedback at certain design stages (FIG. 8). Attached to specific building object(s), the design-related variables can be used to address particular constructability considerations, by different reasoning types.

- *Building* describes the building (or site) level of design information that can help with constructability analysis at very early design phase, including facility type, size, footprint, distance from/to adjacent buildings, and so on.
- *Material* describes the material property sets of an object, including material type, corresponding material properties such as strength and unit weight, and construction-specific requirements such as curing and stripping requirements for CIP concrete. It can be used to address compatibility-related constructability constraints (i.e., material – resource, material – sequence, and configuration – sequence); complexity- and efficiency-related constraints (i.e., design simplification, accessibility, and operation); and coupling constraints. The design decisions regarding material information are usually considered at early design stages (e.g., schematic design) for building systems, indicating potential early constructability feedback regarding system design. While in detailed design, material information can also be considered for assessing reinforcing-related constructability issues.
- *Structural* refers to information specific to structural design and analysis, which indicates the information to be obtained from other sources, for example the structural analysis model, to achieve the computational reasoning. In the case of CIP concrete building structure, “load” is a structural variable that can contribute to constructability. It indicates the basic and expected loading which the structural system or component will need to resist such as the load assumptions (e.g., assumption of live load), and load distribution information (Solnosky & Hill, 2013). In the design process, the loading information helps to plan, analyze, and validate the configuration of structural systems and components from the very beginning, e.g., system level of design, to the end, e.g., element level of design (Solnosky & Hill, 2013). As a result, they are mainly reviewed for configuration – based considerations (i.e., configuration – resource and configuration – sequence; and configuration-based coupling constraints, re-shoring sequence and resource planning, for example (Hurd, 2005).
- *Location* describes the geometric position of an object with respect to the coordinate system, Cartesian coordination system in an IFC model, of its geometric context (Industry Alliance for Interoperability (IAI), 2007). The first (X), second (Y), and third (Z) coordinate of reference points of a component define its location and gives its orientation. As design progresses, the location information is refined through design analysis, which helps construction personnel understand the layout of floor plan and the distance between building components to plan construction activities from early design stages. In return, related constructability feedback can also help designers better determine the location of components.
- *Dimension* of a component, such as length and width, represents the geometric form of the component and describes its shape, such as rectangular. Dimension information was found to allow the following constructability constraints to be addressed: configuration – sequence, configuration – resource, design simplification, accessibility, operation, and configuration- and process- based coupling constraints.
- *Quantity* refers to quantitative design attributes of one object (e.g., one gravity column) or a certain type of objects (e.g., gravity columns), such as count, area, and volume, which can be aggregated to

influence the decisions regarding formwork construction in terms of decisions, such as form reuse. The quantity variables help plan the size and the number of forms, and calculate the ratio of form contact area to total area of formed concrete structure, to determine the efficient use of forms (Hurd, 2005). In addition, the quantity of reinforcement is also considered as an important factor at later design stages to drive more constructible decisions.

- *Relations* captures the relationships among objects, such as connectivity. IFC schema defines two types of objectified relationships within an IFC model: 1-to-1 relationships and 1-to-many relationships. Objects involved in a relationship are named as relating and related object(s). The analysis of the interaction between relating and related objects can help understand the complexity of the project, in terms of repetitiveness, tolerance, and operation, and configuration-based coupling (Staub-French and Nepal 2007, Wood & Gidado 2008).
- *Tolerance* specifies the structural tolerance of building objects, and needs to be considered with construction requirements, to avoid the unnecessary complexity in building specific objects. Rigid tolerance would cause excessive coordination in the field and may increase the set-up time of formwork construction.
- *Other Requirements* helps capture the other design requirements to represent constructability considerations including material/configuration – resource, configuration – sequence, design simplification, and coupling constraints. Those requirements can be finish requirements, curing and stripping time requirements, vibration and fire-rating requirements, and admixture requirements for concrete.

The identification of the constructability links with design information requirements of a CIP concrete structure provides the basis for those elements to be analyzed using automated constructability checking of a given design, in terms of compatibility, complexity and efficiency, and coupling reasoning.

4. VALIDATION

The automated constructability review ontology requires validation to ensure the information links and structures are correct. In this research, two validation steps were performed and will be described in this section. The first step was verifying the ontology that indicates the constructability links with required design and construction information for a constructability review. The second step was verifying the ontology appropriately represented the targeted knowledge for application and use in the context of an automated constructability review.

As the first step, the validation was conducted for the constructability links and required information through a series of expert interviews. Five experts who each have more than 10 years' construction experience in the industry were interviewed, with four of them specializing in concrete construction.

The procedure for validating the constructability links with experts is shown in FIG. 9. The validation procedure started with a brief explanation of the hierarchy of constructability concepts and the captured constructability constraints under each category (FIG. 6); then each constraint with its related constructability links was reviewed. By following the established interview protocol, the experts' feedback on the captured constructability links regarding formwork construction was collected. Depending on the feedback, corresponding actions were color-coded and actions identified for refining the captured constructability links, categorized into seven resultant options (FIG. 9):

- Constraint added: A new constructability constraint was added, to better describe the identified constructability relationship between design and construction information.
- Constraint modified: The constructability constraint was modified, to better describe the identified constructability link, by either refining the name of the constraint or changing to another captured constraint.
- Constraint deleted: The constructability constraint was deleted, when the preliminary constructability link was clarified to be unrelated.

- Link added: A constructability link was added with associated design and construction information, when a piece of constructability knowledge regarding formwork construction was considered important, but missing.
- Link deleted: A constructability link was deleted, when the captured relationship between design and construction information was considered irrelevant with no impact on the constructability of a facility.
- Linked information modified: Information that was linked together to address a particular piece of constructability knowledge regarding formwork construction was considered inaccurate or incomplete and revised to reflect the comments provided.
- No revision needed: The constructability link and associated design and construction information were retained, when the piece of constructability knowledge regarding formwork construction was considered captured accurately.

TABLE 5 summarizes the validation results. Based on the experts' feedback, "repetitiveness," "standardization," "accessibility," and "operation" were the most important design-related constructability constraints for formwork construction, in terms of relieving the complexity and improving the efficiency of production. Regardless of revisions, the 13 constructability constraints were considered inclusive to represent the critical constructability considerations on formwork construction. The generalizability of the captured constructability constraints and relationships were also suggested through examples that were raised by the interviewees, but focusing on other types of projects or system interactions beyond concrete structures and formwork constructability.

TABLE 5: A summary of suggested revisions through experts' interview

Constructability Constraint	***Number of Suggested Revisions***					
	Constraint-related			Link-related		
	Add	Modify	Delete	Add	Modify	Delete
Repetitiveness					1	
Rationalization					1	
Standardization					1	
Accessibility				4	1	
Tolerance					4	1
Operation		2		1	3	
Material – Resources				3	1	
Material – Sequence				1		
Configuration – Resource				3	1	
Configuration – Sequence		2		1	3	
Material-based Coupling				3		
Configuration-based Coupling				3		
Process-based Coupling						

Expectations and challenges of applying the automated approach for a constructability review were discussed with the experts as well. As the timing of the constructability feedback was recognized as critical in providing the full value of a constructability review, a computer-based consistent, checking of design elements was considered beneficial by moving the design-related construction considerations upfront and promoting the constructability communication at the right time to more constructible design decisions. The automated approach was also considered of great value in design for safety review. Challenges were identified in the level of detail of the model content and the representation of some constructability relationships. For example, the lacking details of reinforcing in the interface between a large beam and column make the checking of reinforcing congestion difficult.

The validation interviews continued until no further revisions were noted in the links within the ontology. The slide content used to support the interview process, after all revisions were incorporated, was distributed to all interviewees to verify that revisions occurring after a given interview were verified with all participants.

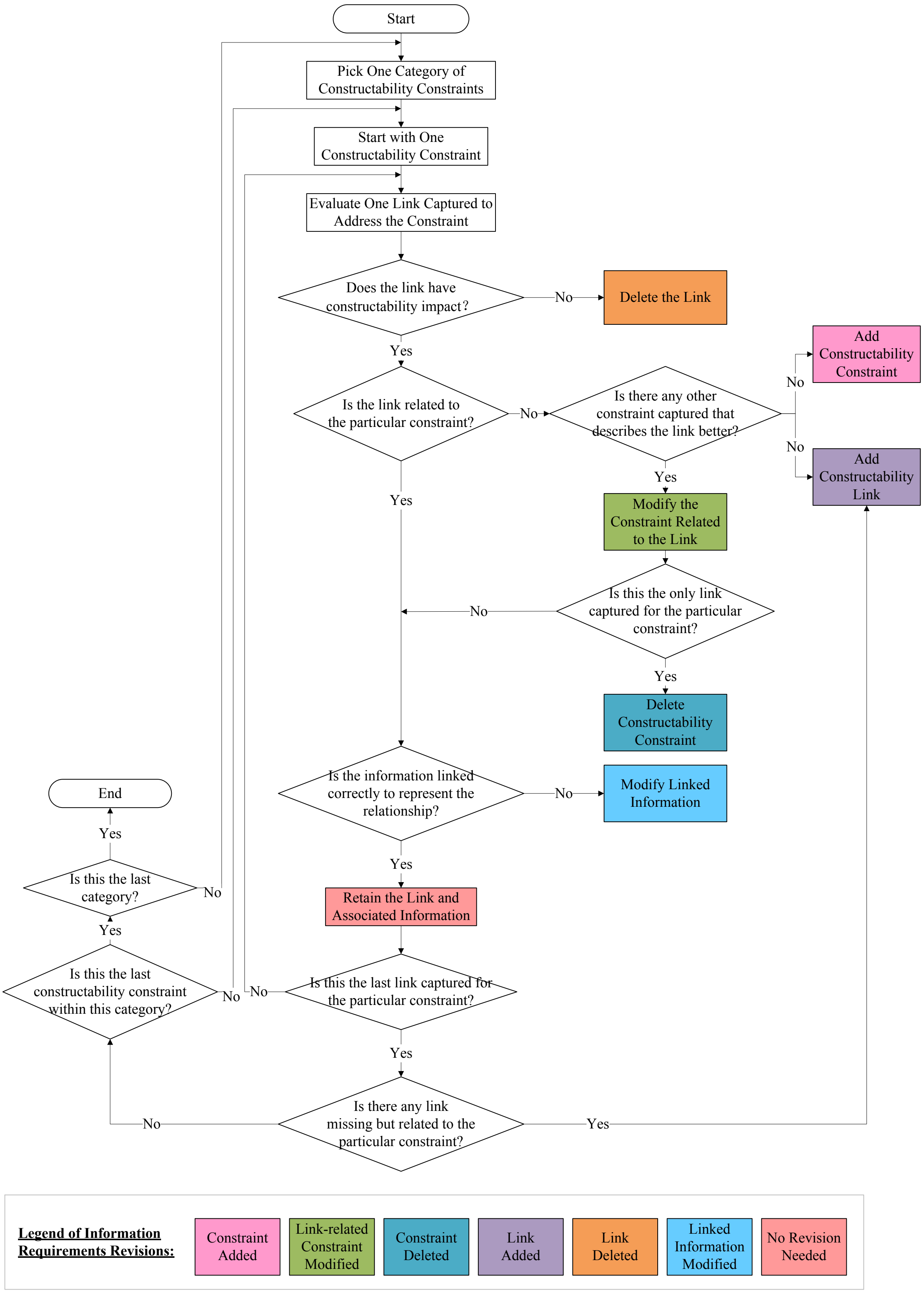

FIG. 9: Validation procedures of constructability links and information requirements

As the constructability links regarding formwork construction were validated, the next step was to ensure the captured constructability links can conceptually be applied for automatically checking constructability of information within a design to support better decision. Jiang and Leicht (2014) used a case study approach and demonstrated the applicability of the rule-based checking for formwork construction. Solibri Model Checker was used as the rule-based platform to test the pre-defined constructability rules with three types of reasoning, which are the object-attribute-value reasoning, reasoning about the relationship among objects, and spatial reasoning. With the rule-based approach, three types of constructability constraints with related links were validated to test the applicability to support decision-making of horizontal formwork systems: Configuration – Resource, Repetitiveness, and Operation (FIG. ***10***).

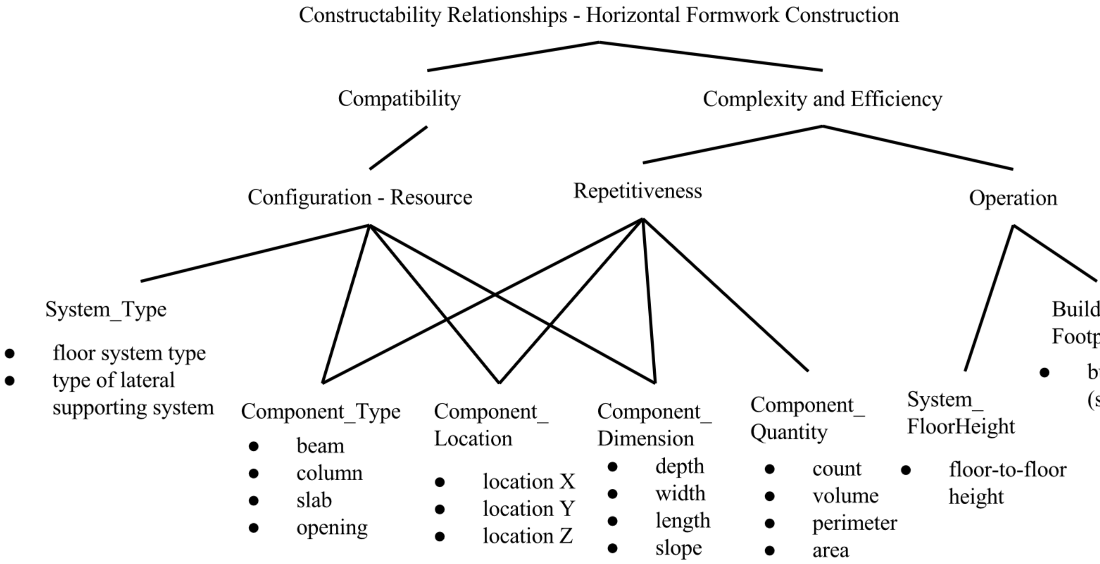

FIG. 10: Validated constructability links with required design information to support decision making of horizontal formwork systems in this case study

The identified constructability relationships helped contextualize the required information of structural objects and the dependency among system information for construction means and methods. The three types of constructability constraints tested in this case study represent two of the three categories of constructability relationships, specifically Compatibility and Complexity and Efficiency. The third type of constraint, Coupling, is difficult to test in this approach as much of the information from the design is extremely detailed and would need to include information from specifications or submittal information, such as concrete mix design. While the relationships are possible to test, the case study data was not available to prototype the relationships for the given project. The feasibility of prototyping the links to support formwork decision-making for the other categories was demonstrated. It presents the ability to prototype the rest of constructability constraints that were validated through experts' interviews, to provide more design decisions support.

Regardless, challenges of representing particular constructability relationships still exist, largely due to technological limitation and the accessibility of modeling information. Technologically, algorithms for sophisticated geometry analysis require more work to investigate constructability problems that can have constructability relationships identified, such as repetitiveness and configuration – resource/sequence. For example, the analysis of layout similarity is still challenging, even though previous research (Staub-French & Nepal, 2007) and available rule-checking programs, such as Solibri Model Checker, show the capability to examine the similarity among components. Some other temporary system specific constructability considerations (e.g., the applicability of flying form for tube system) may need the identification of the component(s) based on geometric characteristics. For example, to help identify the use of a tube system as a feasible option, and then determine appropriate construction methods, the isolation of the columns in the perimeter frame and the spandrel beams is important but requires additional manipulations beyond the simple rule checking currently available through rule-checking software.

The accessibility of the information also causes difficulty in automatically reasoning the constructability relationships, such as accessibility and material – resource/sequence. On one hand, information regarding site and surroundings, material, and details (e.g., connection, reinforcement, and tolerance requirements, etc.) may not be modeled or input in the current design model. Nevertheless, the information is extremely valuable in planning particular material (e.g., self-consolidating concrete) and other accessories (e.g., admixture), crane location and path, interface construction, and many other construction planning concerns. On the other hand, some design information, such as structural loads, may need to be retrieved from other model(s) (e.g., structural analysis model). The access to information such as structural load capacity at early design stages can help offer constructability feedback (e.g., increasing the load capacity of a floor) to reduce the level of re-shoring and benefit formwork construction in terms of less material on site, less density of shores, crane usage, and time for public use. The challenges of current technological capability and the accessibility of modeling information, make the thorough validation of all of the relationships a limitation of the current validation process.

5. DISCUSSION AND CONCLUSION

To conclude, the research focused on formwork construction for CIP concrete structures, and developed an ontology-based approach to capture and define the interdependencies between design and construction information. It allows the interdependencies between system design attributes and construction resource elements to be mapped in the level of detail as design information progresses. With the ontology-based approach, the constructability knowledge can be systematically structured and effectively represented with required design and construction information, greatly enhancing the sharing and re-use of knowledge and collaboration among different project participants. In addition, the constructability relationships with associated information at different level of details were defined. The generalizability and applicability of the relationships in providing constructible design solutions with suggested product design features have been validated. The feasibility of transforming the currently manual constructability review process into an automated process was demonstrated. The new process was found to be a significant move towards Integrated Design and Delivery, in order to minimize the structure and process inefficiencies and enhance the value delivered in constructability implementation.

To transform the traditional constructability review process, the core of automating the constructability review with the use of BIM technology is to enable early constructability feedback for better design decision-making. Instead of a retrospective review, an automated constructability review leans towards proactively bringing the construction constraints into design thinking to impose construction-specific influences on design decisions. The exemplary situation would be checking the design information as design progresses at early stages, so that the constructability concerns that may come later will be incorporated into earlier design decisions. The established constructability ontology formalizes the links between the design information and the constructability concerns, providing the logic and required information for the automated checking. More importantly, construction-specific feedback can be also offered on later design (e.g., floor system design), to minimize the complexity and enhance the efficiency of formwork construction. With the use of the ontology, the constructability links regarding "Design Simplification" and "Operation" point to the constructability thinking of having simple arrangements, such as avoiding drop panels so to have a flat bottom surface of slab, for quicker and easier forming. In turn, the construction-specific feedback serves as input and can be incorporated into later design thinking of floor system and slab-column connections, helping designers and the project team discuss the options and make better decisions. A consistent checking of the constructability concepts will continue reminding the designers and the project team of the alternatives that may be able to enhance the constructability of the project. The consistent checking design information with timing constructability input, however, requires a lot more time and effort in the conventional way of review.

Even though the focus on the current work is temporary systems (i.e., formwork systems), this integrated approach could also be applied to identify constructability issues between two permanent building systems. An example from the intersection between structural and mechanical systems can help demonstrate the applicability of the concept. The chilled water piping is laid out under the roof and supported by strong-backs that are connected to the roofing structure's steel trusses. As a result, the design load of the roofing structure (i.e., structural design variable) should take the point load coming from the weight of the piping (i.e., mechanical design variable) into consideration; the stability of the structure (i.e., "Configuration - Material" constraint under category of "Compatibility") determines the feasibility of the piping installation (i.e., "information" regarding system coordination). Otherwise, the roofing structure may fail, or be broadly overdesigned, negatively impacting the quality, cost, and schedule of the facility. The interaction between the design load requirements and piping layout coordination information in this example can be easily associated with other similar scenarios that might occur between structural and plumbing systems, or structural and architectural curtain wall systems. The ability to generically represent constructability issues of a project design demonstrates the feasibility of applying the ontology to support a constructability review.

Limitations of the current work reside in the scope of the construction systems work, current technological capability, and the accessibility of modeling information. As a result, there are many areas available for further investigations. An extended study can look into the comprehensiveness of the constructability relationships and extend the constructability knowledge to all building systems and all building types. From the perspective of technology development, the means of representing constructability relationships needs further development to implement the proposed process into practice. Shifting to other open platforms, such as BIMServer.org, may provide flexible solutions, though at the expense of greater programming effort to support the model checking goals. Future research can also explore the ways to investigate the implementation of the new processes, for example, applying the traditional and the new review process in parallel and compare the results. The practice of the new process can help thoroughly understand its benefits and the challenge and help continuously improve the value of its implementation to design process and project performance.

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