4th Construction Specialty Conference
4e Conférence spécialisée sur la construction

Montréal, Québec
May 29 to June 1, 2013 / *29 mai au 1 juin 2013*

Virtual Prototyping for Constructability Review

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Abstract: Project design is facing challenges in the Architectural, Engineering, and Construction (AEC) industry. Due to fragmented design and construction process, problems such as change orders and rework occur during construction, resulting in poor schedule and cost performance. The concept of "constructability" has been raised to optimize construction knowledge and experience in the design phase to improve project performance. Previous research has investigated the structure of constructability knowledge and indicated the appropriate level of detail of constructability input should be reviewed at the proper phase of facility design. A few tools have been developed for constructability assessment and analysis, such as knowledge-based systems and quantitative modeling. However, the limitations of such tools have confined the application for constructability review. With the implementation of virtual prototyping in the AEC industry, the current work presents a case study evaluating the applicability of Building Information Modeling (BIM) to constructability review. The current work uses a case study project to collect the different levels of constructability knowledge applied during the project design and analyses the information embedded into BIM model to determine if the appropriate level of detail and information were available to automate portions of the analysis. The procedure of capturing the design-related constructability issues with BIM contents is investigated. Potential benefits of using BIM to facilitate constructability review and decision-making processes prior to construction as a shared knowledge resource are discussed. Implication for practice and future research opportunities are indicated.

1 Introduction

Project design is facing challenges in the Architectural, Engineering, and Construction (AEC) industry. Fragmented design and construction processes have been considered as one of the main causes of the productivity decline in construction (Teicholz, 2004). Problems such as change orders are largely caused by design errors and designers' lack of construction knowledge (Fischer and Tatum, 1997). The impacts of change orders can be disruptive (Jiang et al., 2011). Considering the dependency between design and construction, the concept of "constructability" has emerged. As defined by the Construction Industry Institute (CII), constructability is "the optimum use of construction knowledge and experience in planning, design, procurement, and field operation to achieve overall project objectives," (CII, 1986). The emergence of "constructability" provides substantial opportunities to integrate design with construction and make construction easier, faster, and more cost effective (Fischer and Tatum, 1997; Jergeas and Van der Put, 2001).

With the realization of the potential benefits by improving constructability, many construction companies began to conduct constructability reviews at different design stages in order to improve the reliability of design and facilitate the construction process. Despite the efforts, the application of the right method or constructability tools is still a big challenge (Pulaski and Horman, 2005). Frequently, a review of constructability concepts is adopted by using a checklist and a lessons-learned system after the design reaches a certain design stage, 30%, 60%, or 95% design (Hancher and Goodrum, 2007). It should be admitted that an effective design review can provide helpful feedback to designers to improve the feasibility of construction. However, the large amount of required resources, time and manpower, largely impedes constructability implementation (Hancher and Goodrum, 2007); the rework in design caused by the unsophisticated and inefficient process (O'Connor and Miller, 1994; Pulaski and Horman, 2005) cannot be ignored either.

As the idea of implementing integrated design methods to enhance productivity and value in the industry, the current work examines the existing constructability review process based on a case study project and addresses the research question: *How can we improve the current constructability review process with the help from integrated design methods and tools?* This paper presents a new approach of using Building Information Modeling (BIM) to achieve an automated constructability review, in order to improve the efficiency and enhance the value delivered in the process. The procedure of capturing the structural design-related constructability issues with BIM model contents is investigated. Potential benefits and implications for future work are discussed. The previously relevant research will be reviewed next, indicating the opportunity of implementing BIM to improve the existing process.

2 Background

2.1 Organizing Constructability Knowledge along Project Design

Common sense indicates that constructability knowledge is stored in the heads of construction experts, dispersedly. One of the key elements in constructability implementation is how to organize the constructability knowledge systematically and address the right piece at the right time. Pulaski and Horman (2005) developed a conceptual product process matrix model (CPPMM) to help identify what level of constructability knowledge should be introduced at different design stages, see Table 1. By organizing the constructability information over project delivery process, the CPPMM allows the project team to gauge the appropriate level of constructability input at the proper phase of project design.

Table 1: Part of the Conceptual Product/Process Matrix Model (Pulaski and Horman, 2005)

		Process Model				
		Design				Pre-Construction
		Conceptual Design	Schematic Design	Design Development	Construction Documents	Shop Drawings/ Submittals
Product Model (Level of Detail of Constructability Input)	Building/Site					
	System	System				
	Sub-System		Sub-System			
	Components			Components		
	Elements				Elements	Elements

2.2 Previously Developed Constructability Tools

Previous research has also developed several tools to assess the constructability of a project design and make design decisions. This paper focuses on the constructability tools for better structural design in particular. These tools can be divided into two categories: knowledge-based systems and quantitative analysis systems.

- A knowledge-based system uses a large database to organize the knowledge into a clear structure and systematize the application process (Akerkar and Sajja, 2010). The knowledge-based systems also have two categories: non-graphic based and graphic-based.
    - Non-graphical knowledge-based systems only rely on the database to generate rule-sets for assessment and even automated decision-making. They have been applied to

preliminary structural frame selection (Salazar and Brown, 1988), steel structure design assessment since schematic design (Ugwu et al., 2004), and automated formwork selection for concrete structure at later design (Hanna and Sanvido, 1989).

  - In addition to a database, graphical knowledge-based systems also utilize visual graphics to better address constructability problems and solutions with more details. The visual graphics can be 2-D design used for beam-to-column connections design (Werkman et al., 1990), and computer-aided design for concrete construction methods reasoning (Fischer, 1993) and rebar constructability diagnosis (Navon et al., 2000) at later design.
- Unlike knowledge-based systems, quantitative analysis systems measure the impacts of building constructability on structural design by quantitative modeling. Usually, a constructability score of a given project design is generated. By comparing the score with alternative design options in terms of different construction methods, designers can make decisions and create the most constructible design of a building superstructure at preliminary design (Lam et al., 2007). Other factors that may impact the decision-making process, such as cost (Poh and Chen 1998), and resources usage and labor productivity (CIDB, 1993; Jarkas, 2010), have also been considered.

2.3 Limitation of Previous Constructability Tools

Previous research demonstrates the efforts that attempt to improve the efficiency of the constructability review process. By taking advantage of information technology, the development of those tools is expected to reduce the resources required for the review process and maintain the accuracy of review results. However, they have common limitations, resulting in confined applications in the practices:

- Most of the tools focus on a single aspect of structural design (e.g. a beam design or the usage of a construction method). They investigate the constructability issues of either a system or a component at a time, instead of considering a building design as a whole and meanwhile making necessary trade-offs within the entire system and maximizing the overall constructability.
- The tools merely offer feedback in a “reactive” way. In other words, the feedback obtained from the constructability review and analyses are “after” design, instead of “during” design. According to O’Connor and Miller (1994), this “after-design” assessment requests the construction input too late to be of value and will be likely to impose barriers on the constructability implementation.
- Most tools are separated systems from graphics design and lack the capability of visualization, which can cause communication issues and wastes of time during decision-making (Golparvar Fard, 2006). Communication plays an important part in constructability review process, due to the involvement of different parties. The review tools without visual design can be abstract, which is difficult for communicating and understanding the alternative design options.

Therefore, a more powerful tool will be needed to improve the current constructability review process. It should have the capabilities of visualization, storing design-related constructability knowledge, auto-analyzing potential constructability issues from system level to element level, and providing proactive design feedback from construction perspective.

3 BIM Potentials for Constructability Review

3.1 BIM as A Potential Solution for Integrated Design and Delivery

Building Information Modeling (BIM) has been considered and adopted as a potential tool towards integrated design and delivery, in order to enhance the efficiency and value delivered during design, construction, and operation across projects (Owen, 2009; Rekola et al., 2010). As defined by the National BIM Standard Committee, BIM is “*a digital representation of the physical and functional characteristics of a facility…It serves as a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle from inception onward*” (NBIMS, 2007). The concept of BIM is to “*build a project virtually prior to constructing it physically, in order to work out problems, and simulate and analyze potential impacts*” (Smith, 2007). Instead of a printed set of plans, BIM allows project stakeholders to develop a virtual building information model and exchange the information through collaboration, resulting in better project performance.

3.2 BIM Evolvement in Practices

Since late 1980's, BIM technologies have been adopted and implemented in the AEC industry. Taylor and Bernstein (2007) investigated the adoption of BIM in practices following the paradigm trajectories: visualization, coordination, analysis, and supply chain integration.

- Starting with visualization, BIM displays the building project in a 3D virtual environment. The effective visual representation minimizes the waste in the communication and decision-making process and facilitates the value-adding tasks (Golparvar Fard, 2006) such as evaluating and predicting the effects of a decision on the project.
- With powerful technological interoperability, BIM practices evolve to coordination, analysis, and supply chain integration. Information embedded in BIM models can be shared among project stakeholders and extracted to support their own services. Knowledge-based rule-sets are defined and organized in corresponding programs to detect potential issues for better planning and execution. The practices include automatic conflict checking (e.g. clash detection), engineering analysis (e.g. lighting analysis), and materials tracking. However, a systematic design-related constructability rule-set checking has not been fully investigated.

3.3 BIM as A Potential Tool for Constructability Review

Based on the technological features and emergent practices, the current work proposed a new approach of using BIM to achieve an automated constructability review, in order to improve the efficiency and enhance the value of the process. The implementation of BIM on constructability review process can produce significant potential benefits, in terms of automational, visual, informational, and transformational effects (based on Fox and Hietanen, 2007):

- Instead of a manual check of printed plans with an unsophisticated checklist, an automatic review process will be achieved by well-organized structural design-related constructability rule-sets, which will be stored into appropriate BIM programs. The automatic process is expected to be systematic and comprehensive, reducing the required time and resources to the minimum.
- Unlike most of previous constructability tools, BIM owns strong capabilities of visualization. With 3D graphic representations, potential constructability issues can be easily presented, understood, and communicated among project participants, adding more value to the decision-making process.
- Integrated with 3D graphic representations, the information embedded in BIM models can be extracted and shared among different project parties. The informational effects of BIM implementation allows designers to be aware of design-related construction concerns at corresponding design stages, resulting in "proactive," instead of "reactive," design feedback, and better decision-making.
- As the "proactive" feedback being provided in the design process, the transformational effects will be achieved. The proposed process is expected to push the constructability knowledge into the design process and encourages designers to produce a more constructible design. The rework and change orders due to inadequate constructability implementation should be reduced considerably.

4 Methodology

Case study is adopted as the research strategy to investigate the feasibility of BIM implementation on automated constructability review. The study is pursued in two principle ways: 1) elicitation of constructability knowledge that is necessary to detect and help solve potential constructability issues of a given project; and 2) investigation of the relationship between the constructability knowledge and available BIM contents along the design process. Exploration of the procedures of capturing the structural design-related constructability issues with related BIM contents leads to the conclusions concerning the potentials of BIM for automated constructability review, in terms of automational, visual, informational, and transformational benefits.

Therefore, an on-going building project with a steel structural design was decided to be the case study project. First, a project in progress enables easier access to more detailed project information and documents at each phase, design adjustments along project progress, and the project team. Document review and interviews were conducted to understand the design review process and the structural design-related constructability issues. After face-to-face interviews with principal project team members such as structural designer and project engineer, required constructability knowledge that was stored in the head of the industrial experts was acquired, categorized, and mapped along the design process.

Second, steel structures have more standard design and relatively mature BIM capabilities (Ugwu et al., 2004; Eastman, 2006). More standard design indicates the research results of the case study project are not incidental and can be applied to other steel projects. On the other hand, steel structural projects usually have a complete set of BIM models with relatively consistent BIM content from project participants such as structural designer and steel fabricator, indicating whether adequate information embedded in the existing models at a design stage can be effectively captured to reveal and help solve potential constructability issues.

5 Case Study

5.1 Case Study Project

The case study project is a new dormitory building at The Pennsylvania State University. It is designed with 4 floors above the ground and a basement, with an area of approximately 43,000 square feet (i.e. approximately 3994.8 M^2) and a capacity of approximately 200 beds in total. The building height is 66ft (i.e. approximately 20.12m) high from the lowest grade plane to the mid-height of the roof. The building structure consists of concrete foundation, a gravity system consisting of wide flange steel beams and tube (HSS) columns at each floor, a lateral system with concentric and eccentric braced HSS frames, and cold-formed steel pitched truss roofing. Building floors are designed as the composite concrete slab on steel ribbed deck. Concrete retaining walls are designed at the ground floor, underneath several exterior walls of the building. At the retaining walls, steel columns are supported by concrete piers. Piers and columns are supported by shallow spread footings. The ground floor is a concrete slab on grade.

5.2 Design Review Process

The new dormitory building is being constructed as a Design-Build project. The design work started in July, 2011. Planned durations of design and construction are 8 months and 14 months respectively. In order to ensure the reliability of the design and improve the constructability, the project had subcontractors involved early to review the design as it developed, thus providing constructability feedback (Figure 1). For example, most of subcontractors such as MEP were procured at 50% DD and contracted by the time the Design Development (DD) phase was complete. The design-assist steel fabricator was involved at around 15% Construction Documents (CD) phase (Figure 1) to coordinate with the structural designer and work on the connections design. In addition to subcontractors, the general contractor had its own team to conduct page-by-page design review and offer design suggestions.

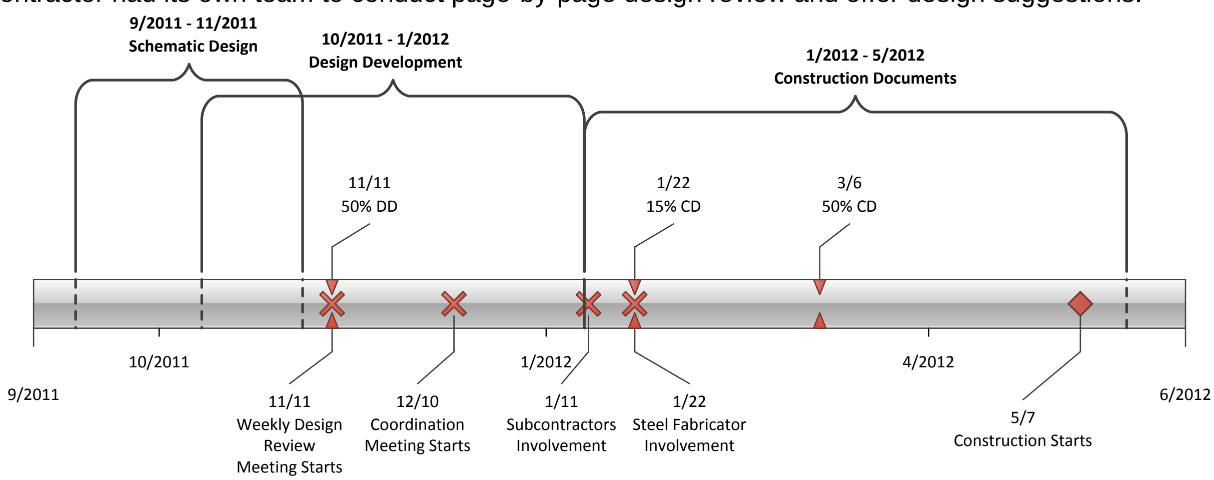


Figure 1: Early Involvement of Contractor and Subcontractors at Design Phase

Weekly meetings began around 50% DD phase (Figure 1), discussing the constructability issues the general contractor or subcontractors found in the design, and feasible solutions. As the BIM models from project participants such as designer and subcontractors were completed (Figure 1), coordination meetings were organized by the general contractor bi-weekly for discussion among the disciplines, such as structural design versus MEP (i.e. mechanical, electrical, and plumbing) design. Major design review comments were documented and sent back to the designer for further consideration. Timely follow-up of the designers' correspondence was made to ensure the constructability of design was enhanced.

5.3 Structural Design-Related Constructability Feedback

By reviewing project documents and interviewing the principal project team members, 20 structural design-related constructability issues were collected and categorized. Table 2 displays the categories of constructability feedback according to 7 different constructability concerns: design inadequacies, design omissions, design ambiguities, design coordination, unforeseen conditions, resource constraints, and performance (Hanlon and Sanvido, 1995; Kirby, 1985). The quantity and an example of constructability issues under each category were listed in the Table 2.

Table 2: Categories of Constructability Issues based on Constructability Concerns

Categories of Constructability Issues		Description	No. of Constructability Issues Which Belong to		Constructability Issue Example
			1 Category	2 Categories*	
Constructability Issues Regarding	Design Inadequacies	Existing design is inadequate to meet the expected performance.	2	1**	Base plate thickness is not thick enough for structural columns to provide structural support.
	Design Omissions	Information of existing design is incomplete.	7	3**	Missing detailed design of roof deck attachment to roof trusses at DD phase.
	Design Ambiguities	Information of existing design is inconsistent.	1		The height of all retaining walls needs to meet 42 inches.
	Design Coordination	Design concerns regarding coordination with other project participants and other disciplines.	6	4**	Coordination with steel design-assist subcontractor is needed for the design of momument stair.
	Unforeseen Conditions	Design concerns due to unforeseen external impacts from/to the environment, the infrastructure, and adjacent sites.	4		Foundation design needs to be changed due to site conditions identified by construction manager (CM).
	Resource Constraints	Design concerns due to resource requirements or impacts, including material, time, equipment and tools, space, etc.	2	1***	The material of wall pier needs to be changed to concrete (Figure 2), due to access constraint.
	Construction Performance	Design concerns based on construction performance, including cost, production rate, quality, safety, etc.	3	1***	Contractor requests to design alternative footing details without drilling dowels into rock due to cost concerns.

*As mentioned, there are 5 constructability issues, each of which have more than 1 constructability concerns;
**4 constructability issues under "Design Coordination" overlap with 1 under "Design Inadequacies" and 3 under "Design Omissions;"
***1 constructability issue has both "Resource Constraints" and "Performance" concerns.

Among those categories, "Design Omissions" and "Design Coordination" have relatively high proportion of related constructability issues. On the contrary, "Design Ambiguities" has the fewest constructability issues. Some of the constructability issues may belong to more than 1 category. For example, the constructability issue- "the material of wall pier needs to be changed to concrete (Figure 2)", considers both resource constraints and construction performance. From the resource perspective, it is infeasible to make 8" x 8" CMU pier at the location in Plan B1 (Figure 2) instead of concrete; from construction performance perspective, it is easier to build such a concrete pier together with the adjacent concrete wall.

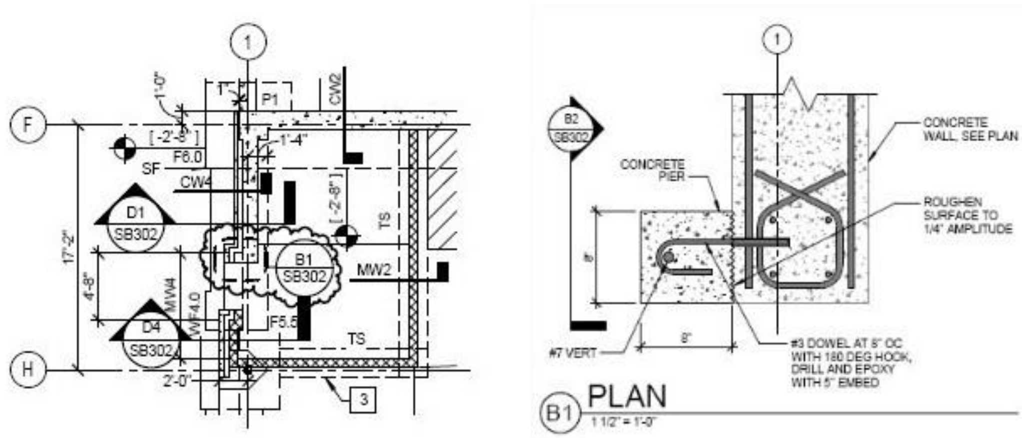


Figure 2: Constructability Issue - “the Material of Wall Pier Needs to Be Changed to Concrete”

Based on the initiatives of constructability feedback proposed by construction experts, those constructability issues can be classified into two categories: reactive feedback and proactive feedback. Different from reactive feedback coming “after” design, proactive feedback will occur in advance to help designers make decisions with timely constructability knowledge input. More value will be added in the “proactive” process (O’Connor and Miller, 1994). Table 3 further describes the differences between the two categories and lists examples of constructability issues under each category. As Table 3 demonstrates, designers obtain more reactive constructability comments than proactive comments. Most of the proactive feedback comes from the constructability concerns of “Design Omissions,” “Design Coordination,” and “Construction Performance.” For example, “missing detailed design of roof deck attachment to roof trusses at DD phase” is describing the element level of design (see Pulaski and Horman, 2005), which is not necessary to be designed at DD phase (Table 1). As a result, the feedback is “proactive,” rather than “reactive.”

Table 3: Categories of Constructability Issues based on Initiatives of Constructability Feedback

Categories of Constructability Issues	Description	No. of Constructability Issues	Constructability Issue Example
Reactive Feedback	Constructability feedback is provided by reacting to a situation, e.g. the design-related constructability problem is detected, or design decision is made.	11	Base plate thickness is not thick enough for structural columns to provide structural support.
Proactive Feedback	Constructability feedback is provided in advance of a future situation, e.g. design-related constructability problem will be detected or design decision will be made.	9	Missing detailed design of roof deck attachment to roof trusses at DD phase.

5.4 Investigation of Relationship between Constructability Knowledge and BIM Contents

Through interviewing the structural designer and contractor, the constructability knowledge that is necessary to realize and help solve the identified constructability issues was acquired. For each constructability issue, the required level of detail of constructability knowledge was then compared with the information in the model of the structural design. Different BIM contents are needed for different constructability issues; consequently, the manner of capturing the BIM contents for different constructability issues are not necessarily the same. Depending on different types of constructability reasoning, pre-defined constructability rule-sets should be able to help extract required information from models and perform automated constructability analysis of a given design. Based on the collected constructability issues, 4 different reasoning types are summarized and listed in Table 4. An IF-THEN statement is used to represent the constructability knowledge and conduct the automated reasoning process. Some examples of the constructability reasoning rules are listed in Table 4 to illustrate the concepts.

Fischer (1993) has demonstrated reasoning about attributes of an object, relationship between attributes of objects, and spatial reasoning; which can extract the information in computer-aided drafting (CAD) models to represent the constructability knowledge and integrate project design and construction methods. Likewise, the three types of reasoning can be applied to BIM as well. As shown in Table 4, a number of constructability issues can be revealed by reasoning about the attributes of a single object. Appropriate value of the properties of the object will be extracted for analysis, the height of the retaining wall for instance. Other constructability reasoning types consider the relationship between attributes of objects and spatial relations between objects, respectively. For example, if the thickness of base plate doesn't satisfy design requirements, there should be "stiffeners" at the base of columns; when the access of a CMU wall pier is not enough, the material needs to be changed from "CMU" to "Concrete" due to resource concern on space constraints (Figure 2).

Table 4: Types of Constructability Reasoning for Automated Constructability Review (based on Fischer, 1993)

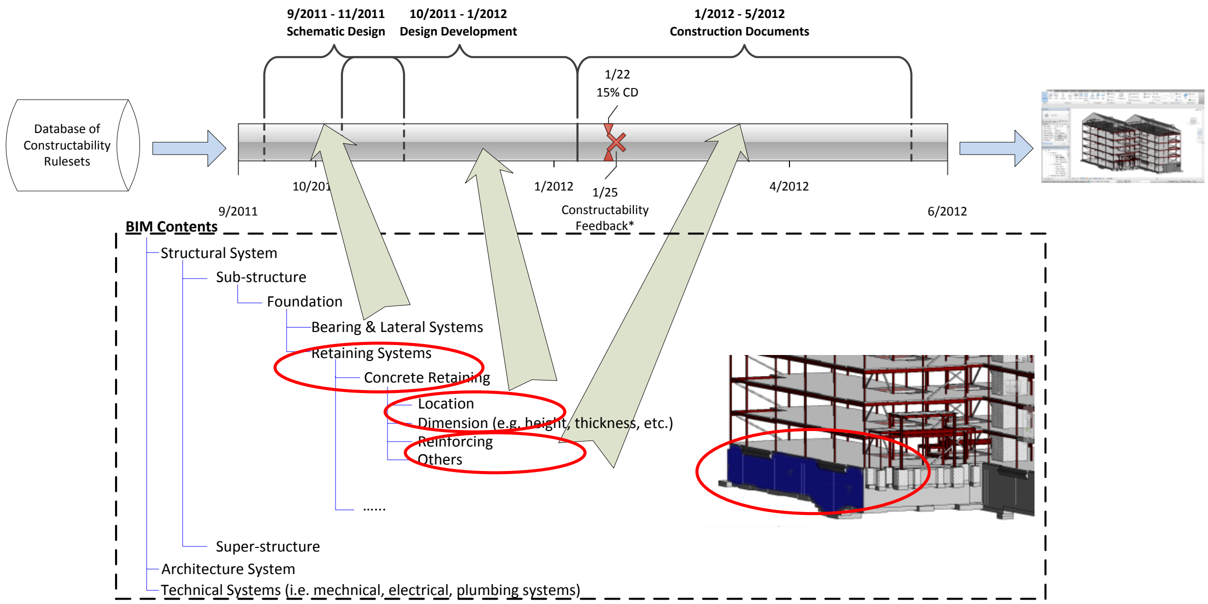
Types of Constructability Reasoning	BIM Contents to be Captured	No. of Constructability Issues	Examples of Constructability Reasoning Rules
Attributes of An Object	location, dimension (i.e. length, width, and height), area, structural type, material, reinforcing, etc.	7	**IF** there is "retaining wall;" **THEN** the height of "retaining wall" needs to be at least 42".
Relationship between Attributes of Objects	attributes of more than one objects	4	**IF** the thickness of base plate is NOT thick enough; **THEN** there should be stiffening element at the base of columns.
Spatial Reasoning	attributes of more than one objects, mainly regarding location information.	4	**IF** the access of a CMU wall pier is NOT enough; **THEN** the material needs to be changed from "CMU" to "Concrete."
Interface Design Progress	connection design section notes, name/type of the objects, etc.	5	**IF** DD phase is TRUE; **THEN** there should be a roof connection design.

In addition to the three types of constructability reasoning, a new reasoning is needed for some constructability concerns on "Design Omissions": reasoning about interface design progress (Table 4). Interface design is very important for structural design so that separate structural components are connected, forming a structural unity to take the load and successfully pass it to the ground. As the design develops, contractors need make sure all the necessary interface design is completed prior to construction. Thus, the existence of connection details between two objects will be examined by constructability reasoning rules of interface design progress, such as "when wall meets the floor, there should be a section note of detailed connection design between the wall and the floor."

5.5 Implementing BIM on Automated constructability Review

The analysis of the constructability knowledge and the reasoning rule of a specific constructability issue determine the required BIM contents to reveal the problem. The capability of BIM allows the pre-defined constructability reasoning rule-sets to be stored in a database of an appropriate BIM tool for future checking. The next step is to apply the rule-sets to a developed BIM model and check if there is adequate information in the model at a certain design stage. Using the example of the constructability feedback the contractor commented on January 25th about the height requirement of retaining walls, Figure 3 illustrates an example of implementing BIM for automated constructability review and whether available BIM contents are sufficient at that time to analyze the constructability issue. Based on Pulaski and Horman (Table 1, 2005), and the hierarchy of BIM contents in Figure 3 (Solnosky and Hill, 2012) indicates the right level of detail of BIM contents of a retaining wall design should be available as design develops.

As illustrated in Figure 3, the contractor raised the constructability concern-"the height of all retaining walls needs to satisfy 42" height requirement" around 15% CD phase when less than half of the retaining walls have been designed, in order to keep the consistency of the entire design and ensure the building codes would be satisfied. The "proactive" feedback was timely and helped to prevent related errors from the main design of retaining walls. However, the “proactive” feedback merely depends on the experience and initiative of construction experts.



*1/25 Constructability Feedback: The height of all retaining walls needs to satisfy 42" height requirement.

Figure 3: An Example of Implementing BIM on Automated constructability Review

With BIM, an automated review will be able to detect the gap between “available” and “required” BIM contents for a specific constructability reasoning rule (i.e. IF there is “retaining wall;” THEN the height of “retaining wall” should be at least 42,” Table 5), providing consistent constructability feedback as design develops like a construction expert with great initiatives. Table 5 also indicates the outcome of the automated review process, transitioning from “proactive” feedback to “reactive” feedback based on the development of level of detail of BIM contents at according design stages. Once a problem is detected by violating the pre-defined constructability rule, the capabilities of BIM will allow the corresponding structural component (e.g. the retaining wall with either missing height information or insufficient height value, Figure 3) to be located and the constructability issue to be visualized, facilitating the decision-making process.

Table 5: Transition from “Proactive” to “Reactive” Depending “Available” BIM Contents

		Property	Value	Design Phase			
				SD	DD	15% CD	100% CD
Constructability Reasoning Rule	**IF**	Layer	"Wall"				
	AND	Name	"Retaining"				
	THEN	Dimension	Height >= 42"				
Available BIM Contents		Layer	"Wall"	√	√	√	√
		Name	"Retaining"	√	√	√	√
		Type	"Basic Wall:Retaining"	√	√	√	√
		Material	"Concrete - Case in Place"	√	√	√	√
		Location	(X,Y,Z)		√	√	√
		Dimension	Height			40%*	√
			Length			40%	√
			Thickness			40%	√
		Other Elements				40%	√
Type of Constructability Feedback by Automated Constructability Review				**Proactive**	**Proactive**	**Reactive/ Proactive**	**Reactive**

* Around 15% CD phase, 40% of the retaining walls have been designed at that level of detail.

5.6 Re-iterate BIM Potentials for Automated constructability Review

In general, the case study demonstrates great potential which BIM offers to achieve an integrated constructability review in terms of automational, visual, informational, and transformational benefits. By applying pre-defined constructability rule-sets, the information in BIM models can be automatically extracted as required to support various types of constructability reasoning. Along the design process, the automated constructability review is expected to perform like construction experts with great initiative and offer consistent "proactive" feedback. 3D graphics representations will help convey the constructability feedback to designers and facilitate the decision-making process. As the constructability feedback is communicated to designers timely and effectively, design rework is consequently reduced and designers are pushed to take the initiative to produce more constructible design.

6 Conclusions

This paper presents a new approach for applying BIM for automated constructability review, in order to improve the consistency and efficiency, and enhance the value, of the existing design review process. Through a case study, constructability knowledge that was needed to reveal the constructability issues was acquired; the relationship between the constructability knowledge and available BIM content throughout the design process was investigated. By categorizing the constructability issues, a new type of constructability reasoning about interface design progress is presented due to constructability concerns on "Design Omissions." Examples of constructability issues were used to demonstrate the potential value of BIM to achieve an automated constructability review, in the perspective of automational, visual, informational, and transformational effects.

Nevertheless, further investigation of constructability reasoning rule-sets is needed. In the case study project, 4 out of 20 constructability issues require constructability knowledge of resource and performance feedback from construction experts (Table 2), which are complicated to acquire and re-structure as constructability rule-sets. Future work will focus on the development of constructability rule-sets and data extraction processes to validate the new approach, and the exploration of heuristic approaches for evaluating resource and performance constraints. Beyond this project's scope, more robust BIM applications for automated user interfaces implementing real time constructability analysis can be explored that implements these rule-sets.

7 Acknowledgements

This paper is based on a case study project at the Pennsylvania State University. We would like to thank the project team for sharing their project information, and taking time to respond to interviews and questions, which led to the valuable contributions of this research project.

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