BIM-BASED MODEL CHECKING IN THE EARLY DESIGN PHASES OF PRECAST CONCRETE STRUCTURES

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Abstract. Designers often carry out their work in the early design stages with disregard to prefabrication requirements, leading to poorly thought out design decisions in terms of precast concrete planning efficiency. If precast expertise could be integrated early into design schemes, this would improve design efficiency, reduce errors and misalignments, and save time at every design iteration. The objective is not to replace precast domain experts, but to help architects make better-informed design decisions. This research is part of a wider investigation that aims to develop a rule-based expert system to support an automated review of precast concrete requirements in BIM models in the early design stages, proactively providing feedback for design decision support. This specific paper summarizes the theoretical part of the research and proposes a way to formalize precast expert knowledge as rule-sets in a tabular form that can be later programmed and integrated in a BIM platform for automated checking of BIM models.

Keywords. Precast Concrete; Rule-based checking; BIM-based model checking; Expert system; Decision tables.

1. Introduction

In the architectural, engineering, and construction (AEC) practice, it is the responsibility of the architect to lead and coordinate an increasingly complex construction process. Much of the rework in the later design stages and on-site frustrations can be traced back to design decisions that lack expert input. If the relevant engineering and construction expertise can be delivered to the architect in a timely fashion, this would allow for better-informed design decisions especially during the earlier phases of design where they have the highest impact. The focus in this research is specifically on precast concrete expertise in the design of modular buildings. Available literature documents problems such as the lack of timely communication between architects and precast manufactures, problems in the precast production stages due to uncertainties in design, and lack of expert precast engineers in design firms (Arditi et al., 2000; Polat, 2008). In addition, lack of awareness of precast requirements in architectural BIM models has been demonstrated in design environments (Sacks et al., 2010). Therefore, there is a definitive need for more rigorous inspection of preliminary design schemes in terms of integrating best practices for precast planning.

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Manually inspecting designs for code requirements in any domain after each design iteration is cumbersome and time-consuming, this raises the demand for more automation. Automated inspections, in turn, rely on computable representations of both buildings and rules represented in the building codes, this is where Building Information Modeling (BIM) offers a practical solution (Nawari and Alsaffar, 2015). In a design checking scenario, BIM can store, manage and apply predefined rule-sets for an automated review process, instead of manually checking designs against individual requirements (Jiang et al., 2013). This paper is part of a research that aims to develop a rule-based BIM expert system to review precast concrete requirements in the early design stages, providing automated feedback for design decision support. Figure 1 displays a basic overview of the proposed system. The paper summarizes the findings of the research up to this point and proposes a way of encapsulating precast expert knowledge in rule-sets in a tabular form that can be later computer-coded in a BIM system. Introduction and related work in CAD applications in prefabrication and precast industry are presented in Section 2 of this paper. Section 3 provides insight into the process of knowledge representation in rule-based expert systems. Section 4 describes the framework of the proposed system and some of the proposed rule-sets. Finally, Section 5 provides the concluding remarks and the course of the future work for this research.

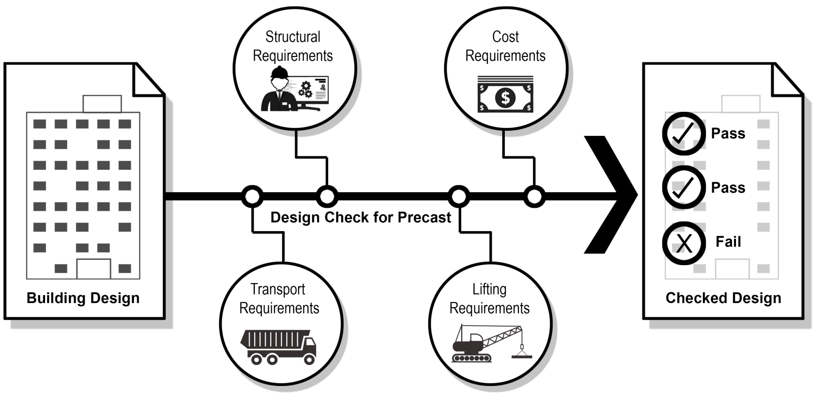

Figure 1. Basic overview of the proposed rule-based expert system.

2. Background

2.1. RELATED WORK

In today's practice, the use of parametric BIM tools is an essential part of the prefabrication and precast planning process. This process, however, still has a great potential for more automation and improvement. Retik and Warszawski (1994) presented a knowledge-based system that receives the preliminary architectural design as 2D drawings and then produces solutions for partitioning the building into modular components, along with the detailed design of these components and their cost estimate. Diez et al. (2007) devised a modular construction software environment (AUTMOD3), comprising a module library of 3D modules and 2D panels, as well as structural specifications and modular division specifications. Using the system, architects can either input architectural plans to be processed to obtain the modules needed for a house design, or they can use an existing catalogue of 3D parametric modules. Costa and Madrazo (2015) implemented a service that pulls BIM models from an open online pre-compiled catalogue of structural precast concrete components in order to assist the design team in the assembly and dimensioning of precast products. Belsky et al. (2016) developed a tool called ”SeeBIM” that enables compiling a set of rules, defined as IF-THEN. The tool tests for topological relationships, and infers new knowledge and details about the model. The authors' prototype implementation was on precast concrete projects.

2.2. NEED FOR AN AUTOMATED RULE-BASED, BIM-ENABLED CHECKING SYSTEM

Most of the reviewed research focused either on design detailing for later design stages or on providing ready-made catalogues of precast components. However, in the early design stages where design decisions have the most profound effect on construction projects, the designer needs to receive expert feedback to decrease the discrepancies that lead to rework without shrinking design thinking to the mere activity of picking pre-made components to assemble in a LEGO-like manner. However, it is worth noting that to define what exactly constitutes “early design stages”, we need to specify the level of development (LOD) of the BIM models to be analyzed. LOD is the degree to which the element's geometry and attributes has been developed (BIMForum, 2016). Five levels of LODs are summarized in Figure 2 (LOD 500 was ignored here because it doesn't represent progression to a higher level of development); this research focuses on models in phase 200, where model elements only have approximate quantities, sizes, shapes, and locations.

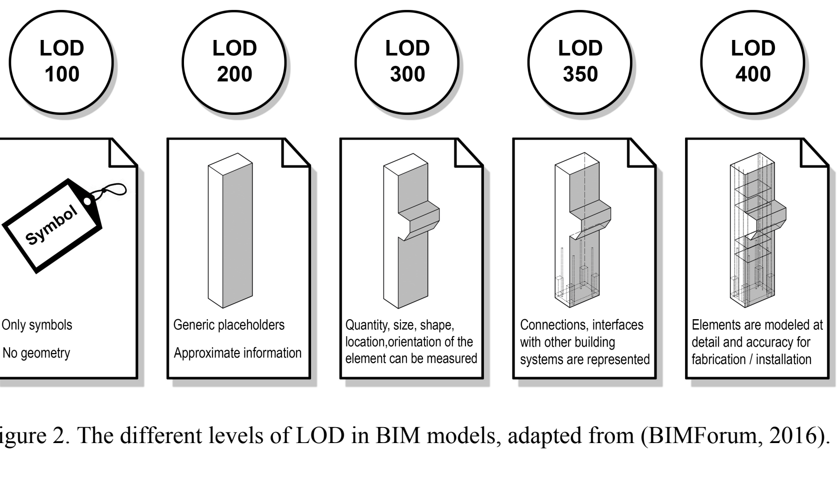

Figure 2. The different levels of LOD in BIM models, adapted from (BIMForum, 2016).

3. Rule-based approach

3.1. RULE-BASED EXPERT SYSTEMS

A rule-based expert system is a knowledge-based computer system that can replace a human expert by making educated guesses using predefined rules, dictating what to conclude in different situations (Adeli, 1988; Grosan and Abraham, 2011). Rule-based expert systems have been proposed as an approach for many domains in the AEC industry: Safety checking in the construction sites (Zhang et al., 2013), tower crane type and configuration selection (Marzouk and Abubakr, 2016), design constructability checking (Jiang and Leicht, 2015), to name a few examples. In terms of the types of interaction with the end user, expert systems could be classified into three types: Critical systems, which evaluate alternatives and give an opinion; dictatorial systems, which assumes the authority of taking decisions directly; advisory systems, which only offers feedback and let the user make the decisions (Grosan and Abraham, 2011). The latter is deemed suitable in the context of this research, because the designer assumes full control of the design decisions, only receiving feedback from the tool.

3.2. KNOWLEDGE REPRESENTATION IN RULE-BASED EXPERT SYSTEMS

A rule-set lies in the heart of every rule-based expert system. At its simplest form, a rule consists of two parts: IF clause (the antecedent or condition) and THEN clause (the consequent or action) (Grosan and Abraham, 2011). This rule-set can then be easily coded into a machine-readable language. To formalize the rules, knowledge has to be solicited from human experts either directly or through literature developed by them, then stored in a data model. It is usually the process of translation of this vague, incomplete, and sometimes contradictory natural language knowledge into formal rules that constitutes the most difficult part of developing a knowledge-based system (Lieberman, 2012). Additionally, compiling these rules merely as consecutive IF-THEN statements becomes less efficient with the addition of more domains and rules. Therefore, we need to establish knowledge representation methods before engaging in the software development phase.

In the context of this research, decision tables were used for the translation of precast knowledge and storing it into formal rule-sets. A decision table is a tabular structure that stores a set of rules in the form of conditions and respective actions (Lieberman, 2012). Decision tables have been used since the sixties for the representation of engineering design provisions (Fenves, 1966), leading to the translation of the AISC specification for the design of structural steel buildings in the United Sates into decision tables (Fenves et al., 1969). Other efforts includes their usage in representing building code requirements for reinforced concrete (ACI, 1973), and seismic design provisions (Wright and Fenves, 1979).

3.3. STRUCTURE OF DECISION TABLES

The basic structure of a decision table is shown in Figure 3. The basic idea is to represent a set of conditions and the actions associated with them. Tables are divided vertically into “stubs” and “entries”. Each column in the table represents a rule, with entries in the “condition” and “action” parts. An entry could be either a “limited entry” or an “extended entry” (Pollack et al., 1972). A limited entry is just a binary value to a Yes/No question in the condition stub. An extended entry enables the introduction of “greater than”, “less than”, “equal to” operators. The “ - ” sign denotes that a value is not applicable in the respective rule. Entries in the “action entries” are either “ - ”, which means, “Do not take this action”, or “X”, which means “Take this action”. An “else” rule should be provided to encompass all the cases that are not handled in the table, if any exists.

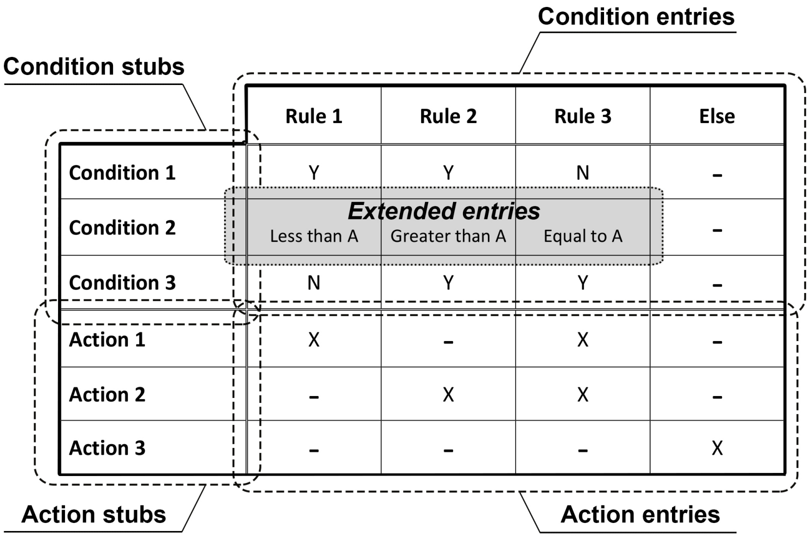

Figure 3. The basic structure of a decision table.

4. Framework of BIM-enabled, rule-based precast concrete requirements checking

4.1. COMPONENTS OF THE FRAMEWORK

This research proposes a framework for a rule-based expert system that checks for precast concrete requirements in BIM design models in the early design stages. Any rule-based system is composed of a few basic components, namely facts, rules, and termination criterion (Grosan and Abraham, 2011). Facts are the input to a system that contains data about the design (in this case the input is BIM models), and what conditions this data fulfills. These conditions, along with formalized precast knowledge that dictates respective actions and termination criteria, are the building blocks of the rule engine and the rule-checking system. The output is a report that presents the results of checking model elements for precast requirements, presenting recommendations for designers. An overview of the proposed framework is shown in Figure 4. The following sections focus only on the formalization of precast knowledge into rule-sets.

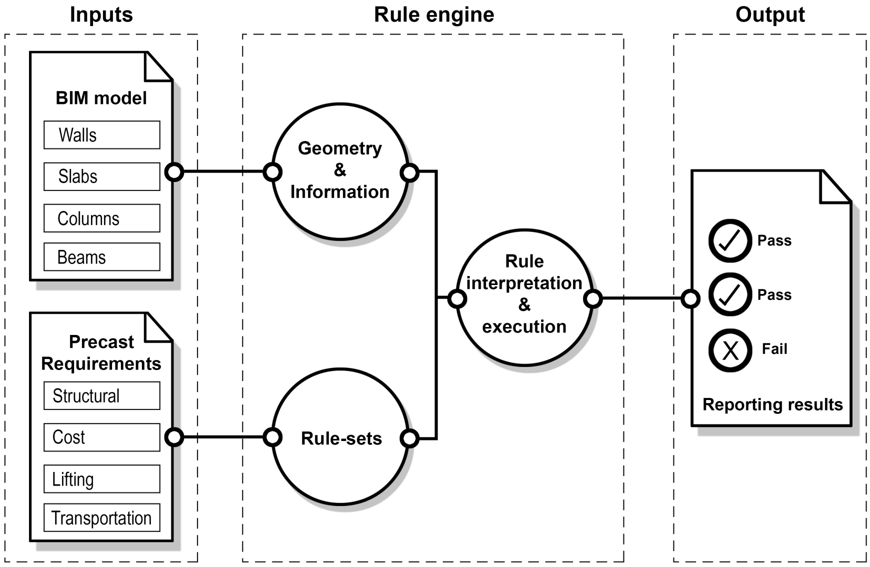

Figure 4. An overview of the proposed framework for BIM-based model checking for precast requirements.

4.2. TYPES OF REASONING FOR PRECAST EXPERTISE IN DESIGN PHASES

To reason about building designs based on precast concrete components as construction elements, we have to understand the types of constructability reasoning in automated systems in the first place. Fischer (1993) classified this sort of reasoning into three types: reasoning about attributes of objects, reasoning about relationships between attributes of objects, and spatial reasoning. Refer to Table 1 for an overview of the three types. Knowledge about the precast requirements has been collected from scientific literature, German DIN specifications, and publications of the German association of precast concrete ("FDB" Fachvereinigung Deutscher Betonfertigteilbau). Due to the size limitation of this research paper, only three examples of decision tables are provided in the next section, one for each type of reasoning.

Table 1. Types of Constructability Reasoning in an automated system (Based on Fischer, 1993).

Types of constructability reasoning	Definition	Example
Reasoning about attributes of objects	Simple comparison between a value of an object attribute to a value from the database	The length of any component should not exceed the value of x
Reasoning about relationships between attributes of objects	Reasoning about the relationship of multiple attributes before comparing a project value with a value from the database	The building use is residential and the span between columns is “a” meters, then the thickness of the slab should be between x & y
Spatial reasoning	Reasoning about a big number of objects, usually in terms of location, orientation, spacing and clearance	Column spacing should be equally distributed to maximize modularization possibilities

4.3. RULES AND DECISION TABLES FOR PRECAST CONCRETE EXPERTISE

Under the “Reasoning about attributes of objects” category, the first example is about inspecting the sizing of individual precast components based on the transportation limitations. According to the German road traffic act (“StVO”), no individual precast element should exceed 15.50*2.55*4.00 meters with no special permission, or 24.00*3.00*4.00 meters with a special permission (Hierlein et al., 2009). This is expressed in the decision table in Table 2. Under the “Reasoning about relationships between attributes of objects” category, the second example illustrates the minimum width of wall panel joints based on the size of the wall panels. This affects the configuration and the size of the reveals on a building façade and should be taken into consideration. This type of reasoning needs a direct or a derived value about other building element(s) before determining an action on the element at hand. In this case, the bigger the size of the panel, the bigger the joint. The exact values are represented in the decision table in Table 3 based on input from (Borchardt et al., 2002). Under the “Spatial reasoning category”, the third and last example relates to the fact that using similar dimensions for precast components enables the manufacturers to reuse the same molds (which are expensive to build), minimizing the total cost of production (PCI, 2010). This means that building designs with evenly distributed column spacing (and floor heights), and similar façade panels are generally recommended. Additionally, the width of hollow core slab units, which are most common in precast construction, is usually 1.20 meters, leading to the fact that the most economical building plan is usually designed with columns centered on 1.20-meter modular grid (Elliott and Jolly, 2013). This is expressed in the decision table in Table 4. It should be noted that there are plenty of other rules relating to the sizing and configuration of precast elements, these rules will be integrated in the framework and detailed in the final research documentation.

Table 2. Decision table to check element sizing for compliance with transport limitations.

	Rule 1	Rule 2	Else	Else
Transport without special license	Y	N	Y	N
Transport with special license	N	Y	N	Y
Length of individual component (m)	≤ 15.50	≤ 24.00	-	-
Width of individual component (m)	≤ 2.55	≤ 3.00	-	-
Height of individual component (m)	≤ 4.00	≤ 4.00	-	-
Display “Element sizing for transport is OK”	X	X	-	-
Display “Warning! Maximum dimensions are 15.50*2.55*4.00 m”	-	-	X	-
Display “Warning! Maximum dimensions are 24.00*3.00*4.00 m”	-	-	-	X

Table 3. Decision table to check for wall panel joint widths.

	Rule 1	Rule 2	Rule 3	Rule 4	Rule 5	Else
Spacing between joints (m)	≤ 2.0	2.0 < x ≤ 3.5	3.5 < x ≤ 5.0	5.0 < x ≤ 6.5	6.5 < x ≤ 8.0	-
Set minimum joint width [w] to (mm)	10	15	20	25	30	-
Display “Please reduce joint spacing to at least 8.0 m”	-	-	-	-	-	X

	Rule 1	Rule 2
Actual joint width ≥ w	Y	N
Actual joint width < w	N	Y
Display “Warning! Minimum joint width is [w]”	-	X
Display “Joint width is OK”	X	-

Table 4. Decision table to check for modularity in the design scheme .

	Rule 1	Rule 2	Rule 3	Rule 4
The columns evenly spaced	Y	N	Y	N
The columns centered on a 1.20 m grid	N	Y	Y	N
Display “Column spacing is optimally configured”	-	-	X	-
Display “Please consider creating an evenly spaced column grid”	-	X	-	X
Display “Please consider using a 1.20m column grid”	X	-	-	X

5. Conclusion and future work

This paper presented a new approach for reviewing precast requirements in construction projects. Instead of introducing precast expertise as an afterthought in the detailed design stages, this expertise can be implemented early when design modifications are easy and less costly, saving both time and effort. An automated rule-based expert system is proposed to check design models, making use of the computability of BIM models, and enabling the possibility of multiple checking rounds to match the iterative behavior that characterizes the design process in the early stages. The result is a report with a list of recommendations to improve upon the design scheme, leaving the final design decisions to the designer. For the rule-based system to be realized, knowledge has to be gathered and formalized in rule-sets that can be later integrated in a computer system. In this research, knowledge has been gathered from scientific literature and industry standards, and formalized in decision tables as the rule representation scheme of choice. Three examples were provided in this paper representing three types of reasoning common in automated constructability review systems. Future work will focus on the translation of these rule-sets to machine-readable code inside a BIM platform and linking them to BIM elements, realizing the proposed expert system.

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