Automation in Construction 64 (2016) 20–26

Contents lists available at ScienceDirect

Automation in Construction

journal homepage: www.elsevier.com/locate/autcon

Formalized knowledge representation for spatial conflict coordination of mechanical, electrical and plumbing (MEP) systems in new building projects

Li Wang *, Fernanda Leite

Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, 1 University Station C1752, Austin, TX 78712, United States

ARTICLE INFO

Article history:
Received 19 August 2014
Received in revised form 6 September 2015
Accepted 28 December 2015
Available online 15 January 2016

Keywords:
Knowledge representation
Design coordination
Conflict resolution

ABSTRACT

Due to the complexity of system configurations, distributed expertise requirements and various constraints, coordination of mechanical, electrical and plumbing (MEP) systems is considered by many construction professionals one of the most challenging tasks in the delivery process of construction projects. MEP coordination is an iterative and experience-driven process, which entails considerable time and human resources. While this process is repeated in every project, there is seldom a systematic way to capture and store the information produced in the process to formalize lessons learned and to support future decision making. This paper presents a formalized schema that can be used to capture clash features and associated solutions during MEP coordination. This representation schema provides a formalized structure for clash documentation to support management of coordination and, more importantly, to capture experiential knowledge to support future decision making. The presented schema integrates findings from previous research, observations from two field studies and a laboratory experiment. The results were validated using project data.

1. Introduction

Design coordination, specifically mechanical, electrical and plumbing (MEP) system coordination is crucial to project success, because it aims to eliminate potential conflicts between systems before field installation. Typically, architecture and structure are designed first, leaving limited space for MEP systems. The MEP design provided by the engineers is usually schematic and requires further development by the specialty contractors with actual sizing of components, additional fabrication details, and finalized locations and routings to meet construction and operational requirements [10,18,25]. When specialty contractors develop their design separately, many coordination problems arise [15].

Current clash detection applications (e.g., Autodesk Navisworks Manage and Solibri Model Checker) have expedited the clash identification process and enhanced visualization capabilities. Nevertheless, the process of analyzing and resolving MEP design conflicts still remains time-consuming and ad hoc. One explanation is that design coordination requires multidisciplinary knowledge, which is often based on experience and is difficult to formalize [10]. Experiential knowledge is usually implicitly carried away by individuals after coordination completion and are seldom explicitly documented and shared with the project team for future benefits. Existing software mainly focuses on progress monitoring in coordination but is not yet sufficient for knowledge management, because it is not clear what information need to be captured and how.

Researchers in this realm [10,23] developed different knowledge frameworks to represent coordination knowledge, which provides a good starting point for this research. However, these knowledge frameworks failed to address the questions of what can be explicitly captured, what needs to be captured and how it can be captured. For examples, how to represent "Aesthetics" and "Safety" in the framework? Is it efficient to congested ceiling plenum may be a critical issue. Furthermore, previous research did not address how to incorporate such knowledge framework in current work practice. Due to these limitations, previously developed frameworks are difficult to apply for knowledge capture and reasoning in current practice. This research develops a knowledge representation schema to capture experiential knowledge during coordination. The captured information can then be reasoned about in a database system to provide future decision support based on collective historical data.

2. Background research

Several researchers indicated the need and potential benefits for capturing knowledge of diverse decision making criteria to formalize a consistent, well-grounded and repeatable method for MEP conflict

---

* Corresponding author at: 2800 Bartons Bluff Ln #1102, Austin, TX 78746, United States. Tel.: +1 512 584 9071.

E-mail addresses: li.wang@utexas.eduand (L. Wang), fernanda.leite@utexas.edu (F. Leite).

http://dx.doi.org/10.1016/j.autcon.2015.12.020
0926-5805/© 2016 Elsevier B.V. All rights reserved.

resolution [8,10,23]. Since this research aims at developing a representation schema for MEP design coordination in a BIM-enabled model-based environment, previous efforts on formalizing MEP coordination knowledge as well as currently available product data classification systems for BIM have been reviewed.

2.1. MEP coordination research

Previous research on MEP coordination can be classified into three main categories, which includes 1) case study research on BIM-enabled MEP coordination, 2) research on coordination cost, effects, and modeling effort, and 3) computer tools for MEP coordination. Case study research on BIM-enabled MEP coordination usually describes the implementation process of using BIM in MEP coordination, the benefits and challenges observed, the best practices identified and the issues and lessons learned throughout the process. Some example studies include the case study of constructability reasoning in MEP coordination [23], 3D and 4D modeling for design and construction coordination [7,22], and collaborative BIM modeling case study [13]. These studies provide evidence of the state-of the-art in MEP coordination using BIM, which shows that the current use of BIM in MEP coordination mainly focuses on automated clash identification, visualization, and communication. Documentation of clashes was usually not described in detail and the process is currently not standardized. Some other researchers investigated cost–benefit relationships between the investment in coordination and field productivity [20], the effects of design coordination on project uncertainty [19], and information requirements for MEP clash identification in manual and automated coordination [14].

The most relevant research regarding knowledge formalization in MEP design coordination was conducted by Korman et al. [10], Korman and Tatum [12], Korman [11] and Tabesh and Staub-French [23,24]. Previous research provides three types of information that are relevant to MEP coordination, which were knowledge items, clash/interference types and solution classes. Tables 1–3 show the results for each, respectively. Table 1 shows a list of knowledge items related to design, construction, and operation and maintenance identified by Korman et al. [10] and Tabesh and Staub-French [24]. Korman et al. [10] identified 13 knowledge items in their knowledge framework. Based on this framework, Tabesh and Staub-French [24] presented a revised version, which included 8 knowledge items from Korman et al.'s framework and added 10 new items. In addition, Korman et al. [10] also mentioned that object characteristics such as geometric characteristics (e.g., coordinate information, component dimensions and connections) and topological characteristics (e.g., location, spatial relationships and spatial adjacencies) need to be included.

Most of the knowledge items identified in previous studies were related to the component itself without much description about the clashing condition. It was found that the only factor that was used to describe the interference was the clash/interference type (as shown in Table 2). The most common classification of clashes was hard clash and soft clash [22,23]. Some researchers also specified the time clash as a third type of clash which is related to clashes that would occur during the construction process [26]. Radke et al. [16] classified clashes into core and envelope clashes, according to the severity of clashes and whether resolution was needed. Korman et al. [10] had the most sophisticated classification: actual (same as hard clash), extended, functional, temporal (same as time clash) and future clashes. Extended, functional, temporal and future clashes are four types of soft clashes.

Previous research provides an initial list of attributes that may be considered for MEP conflict resolution. However, this list needs to be refined since the focus of these studies was clash identification instead of resolution. Furthermore, none of the previous research focused on developing a representation schema to capture clash information and resolution strategies during the design coordination process for future analysis and references. It is important that the attributes can represent relevant knowledge in a model-based environment and can be explicitly documented without adding too much burden to the current work process.

2.2. Knowledge representation schemas and ontologies in the AEC industry

In the AEC industry, a large amount of data is generated and circulated in every project. The industry implementation increase and evolution of BIM significantly augmented the generation speed and amount of model-based data. Ontologies have been used in various fields to build hierarchies of objects with properties and relationships and to reason about them. In the realm of the AEC industry, ontologies have been developed and utilized for information retrieval and knowledge management in previous research projects [3–6,17].

The most mature and widespread building industry domain schema is Industry Foundation Classes (IFC) developed by the International Alliance of Interoperability (IAI), renamed buildingSMART in 2007. IFC is used to exchange model-related data between BIM applications. The IFC specification is written using the EXPRESS data definition language, defined in

Table 1
Knowledge items identified in previous research.

Phase	Attribute	Explanation	Korman et al. [10]	Tabesh & Staub-French [24]
Design	Function	Primary performance function of component	✓	✓
	System	System to which component belongs	✓	
	Material type	Material or choices of material used for specific component	✓	
	Material cost	Cost of component as per vendor data or estimating standards	✓	
	Supporting system	Typical system used to support component	✓	✓
	Insulation	Insulation type and thickness of particular component	✓	✓
	Clearance	Design clearance requirements of components	✓	✓
	Slope	Required slope for component	✓	
	Aesthetic	Aesthetic constraints		✓
	Performance	Performance-related constraints		✓
Construction	Installation space	Space for installation of components	✓	✓
	Installation sequence	Typical installation of components	✓	✓
	Lead time	Average lead time for fabrication of component	✓	
	Tolerance	Difference between design and as-built in architectural systems		✓
	Fabrication details	Fabrication constraints that reflect the practice of industry		✓
	Safety	Safety constraints		✓
	Variance	Difference between design and as-built in MEP systems		✓
	Productivity	Productivity constraints		✓
Operations and maintenance	Access space	Space required for operations and maintenance	✓	✓
	Access frequency	Access frequency required to maintain component	✓	✓
	Performance	Performance-related constraints		✓
	Safety	Safety constraints		✓
	Space	Space consideration imposed to ensure that systems are operational		✓