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Knowledge Formalization and Reuse in BIM-Based Mechanical, Electrical and Plumbing Design Coordination in New Construction Projects Using Data Mining Techniques

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In the Architecture, Engineering and Construction (AEC) industry, inadequate collaboration between project stakeholders and disciplines often leads to conflicts and interoperability issues. Research has been conducted in knowledge formalization to bridge the knowledge gaps and information silos. Formalizing construction knowledge is challenging because most construction knowledge implicitly resides in the minds of construction experts, which is difficult to represent in a formal and explicit manner. The proposed study is built upon previous research findings, and attempts to formalize tacit knowledge in Mechanical, Electrical and Plumbing (MEP) design coordination by capturing necessary information with a model-based information capture system and reasoning about the captured data with data mining techniques. The vision of this research is that the formalized knowledge can be used to provide guidance for early design review incorporating construction considerations, facilitate structured learning from past experience, as well as train novice engineers. In summary, this research has three main contributions. First, this research presents a formalized knowledge representation schema to capture process knowledge in design coordination, which was successfully implemented in a model-based knowledge capture system developed by the author. Second, a model-based knowledge capture system was developed to store clash information in the form of categorized features and link such categorized information directly to the relevant model elements, which can also facilitate organization and management of clashes and supports searching and grouping functions. A prototype system was developed as a plugin to a widely used BIM-based design coordination application and was demonstrated with project data gathered from three new construction projects in the United States. Third, this research applied data mining techniques for knowledge discovery and reuse in MEP design coordination. Classification models were developed to provide predicted solutions for identified clashes based on historical data. The classification algorithms that produced the best results were selected, which reached precision rates of over 70%. The effectiveness of the classification models was tested in a novice experiment.

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Chapter 1 Introduction

This chapter provides an introduction to the targeted problem in this dissertation, summarizes the research objectives and research questions, and describes the organization and structure of this document.

1.1 Problem Statement

Fragmented organizational divisions in the Architecture, Engineering and Construction (AEC) industry and traditional procurement methods (such as design-bid-build) result in an organizational and sequential separation among project stakeholders between project phases. This fragmented nature often leads to information loss, duplication or inaccuracy and further gives rise to productivity loss, schedule delays, cost overruns, increased litigation and unsatisfied production quality (de la Garza et al. 1994; Radke et al. 2009). The annual cost due to inadequate interoperability in the United States capital facility industry in 2002 was estimated at $15.8 billion (Gallaher et al. 2004). The importance of collaboration among project participants and integration between processes has been widely recognized (Gallaher et al. 2004).

One of the most important and well acknowledged collaboration and integration processes is design coordination in Mechanical, Electrical, and Plumbing (MEP) systems. Given that the earlier the changes are made the less their cost impacts will be (Paulson 1976), design review and coordination before construction is crucial to project success by eliminating constructability issues and ensuring design quality before field installation. The general concept of MEP coordination involves defining locations and dimensions of MEP components in confined spaces to avoid interference between pairs of disciplines while complying with design and operations criteria (Korman and Tatum 2001; Korman et al. 2003). Due to the complexity of system configurations, distributed expertise requirements and various constraints, design coordination in MEP systems is considered by many construction professionals one of the most challenging tasks in the delivery process of construction projects (Tatum and Korman 2000; Korman et al. 2003). This challenge has increased in recent years, because the demands for building services (such as air conditioning and fire services) have grown considerably due to commercial and regulatory requirements, while the time given for coordination is not extended, in many cases is even reduced (Radke et al. 2009). Concurrent engineering has been applied to reduce development lead time through performing activities in parallel, but also leads to more defects (Handfield 1994), which adds to the challenge for collaboration. When specialty contractor develop their design separately, many system coordination problems arise (Plume and Mitchell 2007).

In the past, design and construction typically relied on drawings and specifications which are usually two-dimensional (2D) and paper-based. MEP design coordination was performed by overlaying two-dimensional drawings on a light table; and contractors/subcontractors visually identified design conflicts. This is known as Sequential Composite Overlay Process (SCOP) (Korman et al. 2003), and is very time-consuming and error-prone (Tabesh and Staub-French 2006; Leite et al. 2011). After conflicts are identified, the team jointly develops a solution that works for all parties involved. When manually performed by a team of specialty contractors led by a general contractor (GC), the coordination process can be painstaking. Each trade has its own priorities and strong incentives to make their respective work assignments as easy as possible for their crews to perform (Riley 2000).

As technology evolves and 3D parametric modeling being successfully adopted in the manufacturing industry, digital representation of building information has gradually gained its recognition in the construction industry and becomes widely applied nowadays. This new process is known as Building Information Modeling (BIM) or Virtual Design and Construction (VDC), which gives rise to a revolutionary paradigm shift in the AEC industry. The advancement of information technology is changing the way people work, think and communicate. Nowadays, BIM has been widely used in the construction industry in the United States, mostly for design or trade coordination (Hartmann and Fischer 2007; Becerik-Gerber and Rice 2010). With the assistance of BIM, the construction team can perform automated clash detection to identify clashes between systems more efficiently and intuitively, as compared to paper-based design review (Songer et al. 1998; Staub-French and Fischer 2001; Staub-French and Khanzode 2007; Khanzode et al. 2008; Leite et al. 2011).

The advantages of BIM processes and applications have been well discussed by the researchers and practitioners throughout the years. One of the most applied and rewarding BIM applications is model-based design coordination. However, despite of the expedited clash identification process and enhanced visualization capabilities, the process of resolving MEP design conflicts is still very time-consuming and ad hoc. One explanation is that design coordination requires multidisciplinary knowledge, which is often based on experience and difficult to formalize (Korman et al. 2003). Experiential knowledge and lessons learned for design coordination are usually implicitly carried away by individuals after project completion and are seldom explicitly documented and shared with the project team for future benefits. The lack of formalized knowledge for MEP design conflict resolution hinders the attempts towards streamlining and expediting the decision making process, and also impedes knowledge reuse and transfer.

1.2 Motivating Case

In order to better understand the current state of practice in BIM-based design coordination and further explore the targeted problem, I conducted a case study on a construction project as a motivating case for this research. This is an expansion project on the High Performance Computing Facility for the Texas Advanced Computing Center (TACC) at the University of Texas at Austin. The project started in October 2011 and was complete in August 2012. The expansion project provides approximately 10,000 gross square feet of high density data center space adjacent to a current existing building. The project includes 6.2 MW of power, 3,700 tons of cooling and an 8,000 square foot stand-alone central plant. The procurement method was Construction Management at Risk (CM at Risk). Because of the complex Mechanical, Electrical and Plumbing (MEP) systems involved, successful design coordination became critical, which was also the reason why this project was selected as a motivating case. Sources of evidence for this case study included semi-structured face-to-face interviews, document analysis and field observations. Interviews were conducted with the project manager, superintendent and BIM coordinator during the preconstruction phases. Documents analyzed included the federated Building Information Models (BIMs) that combined architectural, structural, MEP and fire protection models, shop drawings, design specifications, meeting minutes, construction schedules and Requests for Information (RFIs). On-site observations included weekly owner meetings, foreman meetings and design coordination meetings from November 2011 until March 2012.

1.2.1 Design coordination process

In the design phase, the design team developed Construction Documents (CDs) including 3D design models, 2D drawings generated directly from the models, technical documents and specifications. In the preconstruction phase, the subcontractors were given access to the 3D models and 2D drawings prepared by the design team. All design models were distributed to team members using Accellion's web-based file transfer service. The subcontractors used the 3D design models as references to create fabrication level models (also referred as construction models) for their respective scope of work. In some cases, subcontractors may change the system design when the designers leave the choices to the contractors. The responsibility and flexibility is left to the contractors and subcontractors for designing system details. In this project, it was required that every element above 1" (approximately 2.5cm) diameter should be included in the fabrication models, while design models only included mechanical piping over 3" (approximately 7.6cm). Detailed layout of the fire protection system was not provided in the design model. Clearance zones were also modelled in the fabrication models, which included code-required clearances, access zones and other spaces that should be left empty. Figure 1 shows an example of code-required clearance zones that were modelled around the electrical panels. Figure 2 shows an example of access clearance required by mechanical equipment. The yellow objects represented the access zone and swing area around panel doors.

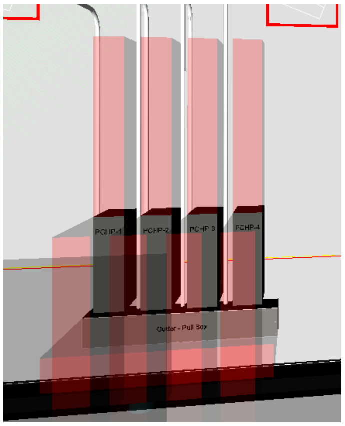

Figure 1: Clearance zones modelled around electrical boxes

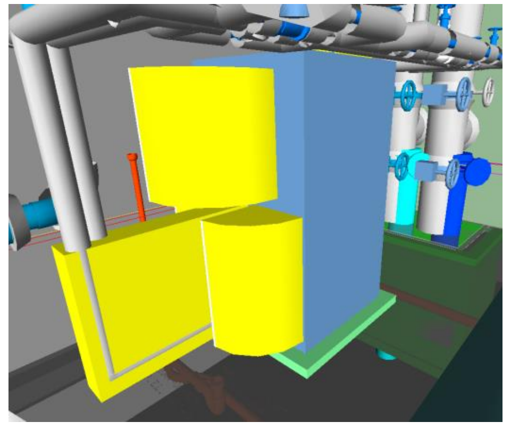

Figure 2: Access zones and swing area around panel doors

Design coordination of the fabrication level BIMs was led by the general contractor (GC). The GC developed the BIM implementation plan to specify requirements on the targeted BIM uses and delineate roles and responsibilities of each company. A BIM coordinator was assigned to organize and lead the coordination meetings. Before every meeting, the BIM coordinator combined the latest models received from the subcontractors into a federated model and ran automatic clash detection using Autodesk Navisworks Manage 2011. Thousands of clashes may be found by automatic clash detection. According to the BIM coordination in the project, nearly 50% of the clashes identified automatically were false positives. The most import step was to clean out the false positives and highlight the real clashes which were then discussed at coordination meetings.

Design coordination meetings were held every Monday, Wednesday and Friday mornings. In the meetings, the BIM coordinator went through the clashes in a specific scope (specified in the coordination schedule) with the subcontractors and the team came up with an optimal solution to resolve each clash. Clashes identified from the models were documented as “Saved Viewpoints” in Navisworks which contained a snapshot of the clash (sometimes with annotations and markups) and a brief description (as shown in Figure 3). Requests for Information (RFIs) were issued to the design team when clarification was needed or major design changes were proposed and needed to be approved. After each meeting, the subcontractors addressed the changes assigned to them, updated their model and sent the revised model back to the GC for another round coordination until there were no additional changes to be made. Once the coordinated model was approved by the project team, shop drawings were produced for fabrication. Models were typically signed off by floor level.

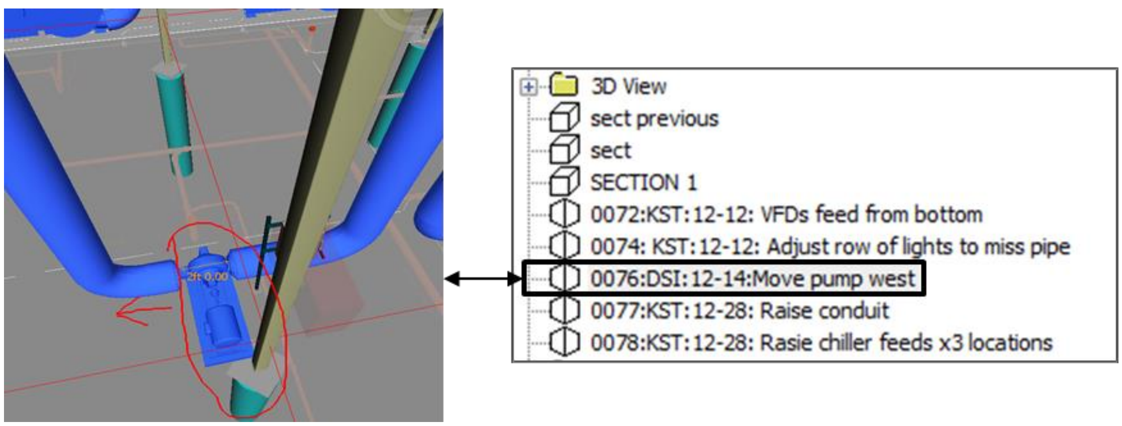

Figure 3: An example of clash documentation using “saved viewpoints” in Navisworks

1.2.2 Research challenges identified from the motivating case

Several challenges were identified from the design coordination process in the motivating case and are discussed subsequently.

(1) Inadequate documentation of coordination information

From the motivating case, it was observed that the information generated during the design coordination process was either not documented at all or not properly documented. In most cases, the BIM coordinator posed an issue and the construction team devised a solution, which would be represented in an updated model. As long as the clashes are resolved, what changes are made and why those changes are made are not the questions valued by the construction team. Many changes were only represented in an updated model and reside in the minds of associated participants. If the knowledge is not documented, it is difficult to learn from it. Since design coordination is an iterative process, it can be considered as a source for gathering coordination data and formalizing knowledge. The information generated in the design coordination process, if being documented properly, can be utilized as basis for knowledge formalization. Thus, guidance needs to be provided on what information items should be documented and the preferable format for documentation.

(2) Insufficient management of documented clash information

Clash information was not stored in the way that can be easily managed or used for future references. Some were stored in the comment string in viewpoints, others as text markups or in clash reports not linked directly to the model. For example, comments on clashes were stored as the title of saved viewpoints in Autodesk Navisworks, represented as a String. For this reason, it is difficult to search, filter, or organize the documented information by specific characteristics (e.g., filtering all issues related to the Fire Protection system). Since there is currently no clash representation schema, most of the currently available markup tools only support commenting on saved viewpoints, which makes organizing or filtering clashes by features a tedious task.

(3) Loss of experiential knowledge

Design coordination involves intensive tacit knowledge from different domains. The majority of clash resolution decisions were made using collective knowledge from multidisciplinary professionals. The efficiency of the coordination process and the accuracy of results largely depend on the expertise of specific individuals involved. The lessons learned from the review process was usually implicitly carried away by certain individuals rather than shared with the project team. Although the information captured during the coordination process may not explicitly represent the expert knowledge, it provides a data source for further reasoning and knowledge exploration. Such experiential knowledge will help guarantee that novices or people not directly involved in a process will be able to more quickly learn what they need to know, and when people leave, not all their knowledge will be lost.

1.3 Research Objectives and Research Questions

The proposed study aims at formalizing tacit knowledge in design coordination by capturing necessary information with a model-based information capture system and reasoning about the captured data with data mining techniques. It is envisioned that by capturing and analyzing historical data relevant to coordination issues, tacit knowledge of MEP design conflict resolution can be semi-automatically extracted and formalized, which will reduce the reliance on individual researchers for knowledge formalization.

The primary objective of this research is to develop a data-driven knowledge formalization approach for MEP design coordination in new construction projects. Secondary objectives are to use the formalized knowledge to improve coordination efficiency, facilitate structured learning from past projects, provide guidance for design improvement, as well as train novice engineers/coordinators. The following research questions have been developed in support of the research objectives.

Question 1. What are the attributes that have significant influence on clash resolution in MEP design coordination and can be explicitly captured?

Question 1.1 What are the typical decisions that need to be made during MEP design coordination?

Question 1.2 What are the important attributes/factors to consider in MEP clash resolution?

Question 1.3 What attributes can be explicitly captured and represented in a computer-interpretable manner?

The first research question addresses the knowledge elicitation aspect of this research. The answer to this question will help determine what needs to be captured in the proposed data-driven knowledge formalization system. The result is presented as a knowledge representation schema. Detailed discussion can be found in Chapter 2.

Question 2. How to capture and represent data for identified attributes in a model-based environment with information technology support?

Question 2.1 How can information be properly captured so that they can be easily accessed and reasoned about?

Question 2.2 What are the limitations of current documentation approaches? What additional features are desired and how can these be achieved?

The second research question addresses the knowledge formalization aspect of this research. The answer to this question will provide explanation on why current documentation approach is not sufficient to support the knowledge formalization purpose and an advanced approach to capture the information identified in Research Question 1. A prototype system was developed demonstrate the proposed knowledge capture approach. Detailed information can be found in Chapter 3.

Question 3. What knowledge can be extracted and reused using the captured information?

Question 3.1 How to reason about the formalized knowledge using data mining? What learning algorithms can be used?

Question 3.2 How effective is the proposed data-driven decision support system in assisting novice coordinators?

The third research question addresses the knowledge deployment aspect of this research. Once the relevant information is captured, the next questions are what knowledge can be extracted and how can we reuse the formalized knowledge. The results are shown in Chapter 4.

1.4 Reader's Guide to the Dissertation

This PhD dissertation is organized into five chapters. Chapter 1 presents the introduction, motivating case, research objectives and three research questions. Chapters 2, 3, 4 address Research Questions 1, 2, 3, respectively, with each of these chapters written as stand-alone documents that contain an introduction, literature review, research method, results, and conclusion sections. Chapter 5 summarizes the dissertation's conclusions and findings as well as limitations and provided suggestions for future research.

Chapter 2 Formalized Knowledge Representation for Spatial Conflict Coordination of Mechanical, Electrical, Plumbing (MEP) Systems in New Building Projects

This chapter presents a formalized clash representation schema that supports clash documentation and management in Mechanical, Electrical, Plumbing and Fire Protection (MEP) design coordination in building projects. The representation schema captures clash features and associated solutions. It 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 with experts using a recognition-based method.

2.1 INTRODUCTION

Construction projects are usually accomplished through several sequential phases. Each phase involves multiple parties such as owners, architects and engineers (A/E), contractors, subcontractors, materials and equipment suppliers. These parties, with various organizational backgrounds and cultures, are dispersed both geographically and over time. The fragmented nature of the Architecture, Engineering and Construction (AEC) industry results in a sequential and cultural separation between different disciplines and project phases. The information silos and inadequate collaboration between disciplines often lead to information loss, duplication or inaccuracy and further give rise to productivity loss, schedule delays, cost overruns, increased litigation and unsatisfied production quality (Fischer 1991; de la Garza et al. 1994; Alarcón and Mardones 1998; Gallaher et al. 2004). The annual cost due to inadequate interoperability in the United States capital facility industry in 2002 was quantified to be $15.8 billion (Gallaher et al. 2004).

Design coordination is one critical process to ensure that no conflicts exist between different systems spatially or functionally before field installation. One fundamental yet challenging task in design coordination is the spatial coordination of Mechanical, Electrical and Plumbing (MEP) systems (Riley 2000; Tatum and Korman 2000; Korman et al. 2003). The general concept of MEP coordination involves defining locations and dimensions of MEP components in congested spaces to avoid interference between pairs of disciplines while complying with design and operations criteria (Korman and Tatum 2001; Korman et al. 2003). Typically, architectural and structural systems are designed first, leaving limited space for MEP systems. MEP engineers/design consultants provide schematic designs of MEP systems layout and routing; specialty contractors are then responsible for finishing the detailed design by specifying sizes and locations of ducts and piping, fixtures, and equipment (Riley 2000; Korman and Tatum 2001). Traditionally, when design drawings were only drafted in 2D, MEP coordination was usually conducted by general contractor and specialty contractors sequentially overlying shop drawings of different systems on a light table and visually identifying constructability issues. This process is known as Sequential Composite Overlay Process (SCOP) (Korman et al. 2003). The 2D-based design coordination process is very time-consuming and error-prone, and the information generated during the process is difficult to capture and store for future use (Leite et al. 2011).

In recent years, the widespread adoption of Building Information Modeling (BIM) and 3D modeling in the AEC industry has dramatically changed the way construction professionals work, think and communicate. Nowadays, BIM has been widely used for design coordination in building projects in the United States, especially in the fast pace and mechanically intensive facilities such as data centers, hospitals, and laboratories which require intense coordination efforts (Riley et al. 2005; Hartmann and Fischer 2007; Becerik-Gerber and Rice 2010). With the assistance of BIM, the construction team can perform model-based clash detection more efficiently and intuitively, as compared to paper-based design review (Songer et al. 1998; Staub-French and Fischer 2001; Staub-French and Khanzode 2007; Khanzode et al. 2008; Leite et al. 2011). There are several commercially available software applications that enable model checking and model-based clash detection (e.g., Autodesk Navisworks Manage, Solibri Model Checker, Bentley Navigator, and Tekla BIMsight). Although the efficiency of collision detection has been greatly improved, the collision resolution process is still very iterative and experience-driven. Decision making during MEP coordination still heavily relies on expertise and judgments of individuals. Similar coordination issues keep occurring throughout the project and in multiple projects. Current practices fail to address the challenge of capturing clash information and solutions in a standardized and computer interpretable manner so that historical records and knowledge can be referenced and reused in future projects. A great portion of construction knowledge is generated and used in the coordination process, which is usually lost afterward, but can be utilized if systematically documented (Wang and Leite 2012). A more efficient and effective lessons-learned and knowledge management system is needed.

In current practice, coordination information is partially documented in the forms of clash reports, tags or comments attached to coordination models or in informal documents. This information is mainly used for communication purposes. Since what should be documented remains ill-defined and the information is not documented in a way that can be easily managed or referenced in future projects, it is difficult to utilize the documented information to formalize knowledge or assist future decision making.

Therefore, experiential knowledge mainly exists in the minds of individuals involved and is hard to explicitly share and reuse. The first step to overcome this challenge is to develop a representation schema to capture coordination knowledge. It is envisioned that formalized coordination knowledge can be used to provide guidance for designers to incorporate construction as well as operation and maintenance (O&M) considerations in early design, to provide decision support for novice coordinators, or to narrow down the search space for experienced coordinators.

Previous research mainly discussed the visualization strength of BIM in design coordination (Riley 2000; Kamat and Martinez 2007; Staub-French and Khanzode 2007), while limited research tackled the challenge of developing a formalized knowledge representation for design coordination, especially for clash resolution (Radke et al. 2009; Tommelein and Gholami 2012). This paper presents a representation schema with a focus on MEP systems coordination in building projects. The representation schema captures information that describes spatial conflicts identified in the federated model and the solutions/actions taken to resolve such conflicts. This schema provides a formalized structure to capture past project data during design coordination for future data reuse.

2.2 Literature Review

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 resolution (Korman et al. 2003; Tabesh and Staub-French 2005; Khanzode 2010). 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.

2.2.1 MEP coordination research

Previous research on MEP coordination can be classified into three main categories, which includes 1) research on case study research on BIM-enabled MEP coordination in projects, 2) research on coordination cost, effects, and modeling effort, and 3) research on 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 (Tabesh and Staub-French 2005), 3D and 4D modeling for design and construction coordination (Hartmann and Fischer 2007; Staub-French and Khanzode 2007), and collaborative BIM modeling case study (Kuprenas and Mock 2009). 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 (Riley et al. 2005), the effects of design coordination on project uncertainty (Riley and Horman 2001), and information requirements for MEP clash identification in manual and automated coordination (Leite et al. 2009).

The most relevant research regarding knowledge formalization in MEP design coordination was conducted by Korman et al. (2003; 2006; 2009) and Tabesh and Staub-French (2005; 2006). Korman et al. (2003) identified three knowledge domains (i.e. design criteria and intent, construction issues, and operations and maintenance) that are important for MEP coordination and the knowledge items related to each domain. The attributes identified by Korman et al. (2003) include geometric characteristics (e.g., coordinate information, component dimensions and number of connections per length) and topological characteristics (e.g., location, spatial relationships and spatial adjacencies). Based on this framework, Tabesh and Staub-French (2005) further classified the MEP coordination tasks into conceptual reasoning coordination tasks (i.e., design validation, detailing, and sequencing) and spatial reasoning coordination tasks (i.e., layout, routing and positioning) and the underlying reasons behind the constraints identified in each discipline (i.e., tolerance, productivity, space, performance, access, safety and aesthetics). 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. There is also a need to integrate the identified knowledge items with the product model currently used for coordination.

2.2.2 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 (El-Diraby and Wang 2005; Rezgui and Zarli 2006; El-Gohary and El-Diraby 2010; El-Gohary and El-Diraby 2011; El-Diraby 2013).

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 ISO10303-11 and embeds a wide range of building information throughout the building life cycle (Grobler et al. 2008). However, there is no adequate support for design coordination in IFC, especially clash resolution documentation. The newly released IFC 4 initiated specific support to capture the result of a clash with a new class IfcRelInterferesElements, which indicates inference between two elements (buildingSMART 2013). The attributes defined in this class are limited (RelatingElement, RelatedElement, InterferenceGeometry, InterferenceType and ImpliedOrder). These attributes are not sufficient for capturing clash resolution decisions.

The OmniClass Construction Classification System (known as OmniClass™ or OCCS) is a classification system for the construction industry which provides a strategy to classify and organize building information. OmniClass has fifteen tables representing different types of construction information. The tables that are relevant to the MEP design coordination include Table 21-elements, Table 23-products, Table 33-disciplines, Table 34-organizational roles, Table 41-materials and Table 49-properties. The information captured by IFC and OmniClass includes geometric and functional information of model components and will be used to describe relevant model features of a clash scenario.

The BIM Collaboration Format (BCF) is a recently developed XML schema, to encode messages that inform a software package of issues found in the BIM model by another software tool (buildingSMART 2014). At its current stage, the markup.xsd schema in BCF supports storing textual information about a topic in the comment attribute, which contains free text to describe an issue. Such information in the free text format is sufficient for communication purposes, but since it does not ensure the consistency of information content, it is difficult to be used for further analysis.

2.3 Research Approach

A three-step process was used for the development of the representation schema, which includes: 1) literature review; 2) field study, and 3) laboratory experiment. Previous research has summarized important knowledge items in MEP coordination, which provides an initial list of attributes for consideration (Korman and Tatum 2001; Korman et al. 2003; Tabesh and Staub-French 2005; Tabesh and Staub-French 2006). The initial list of attributes was then examined for the purpose of representing coordination knowledge which can be easily incorporate into current work practices.

Two field studies were conducted on two construction projects. Project A is a 120,000 square feet, five-story medical office building, which broke ground in July 2012 and finished construction in early 2013. Project B includes a new 7,706-seat football stadium and a 107,613 square feet Student Union Center adjacent to the stadium, which started construction in March 2012 and reached substantial completion June 2013. One of the authors participated in the coordination meetings of both projects for three months. Information discussed and documented during the coordination meetings was captured. Follow-up interviews with the BIM coordinators provided further information for clarification and supplement. The field studies, to some extent, revealed the current practice of MEP coordination in projects, which helped the authors develop a representation schema that can support live capture of coordination knowledge during coordination meetings. The limitation of field studies is that it is difficult to understand the thought process of experts during coordination, while after-the-event investigation might not provide sufficient and accurate information about the reasoning of decisions made because of the time lag.

A laboratory experiment was conducted to overcome this challenge. Six experienced coordinators participated in this experiment. The experienced coordinators had between 3.5 and 12 years of project experience in MEP design and/or coordination and represented six different construction companies or general contractors (GCs) that specialized in office buildings, healthcare, institutional facilities, heavy civil, transportation, oil and gas, mining, data center and commercial construction projects. Participants were asked to look through a series of pre-defined clash scenarios, provide suggestions to resolve the clashes, and prepare a clash report for a hypothetical coordination meeting. Fifteen clash scenarios were selected from a federated model for an office building of a healthcare project in Texas. The experiments were conducted on a one-to-one basis through face-to-face interaction or via a web conferencing system where screens could be shared and controlled by participants. The same experimenter led all sessions following a standard protocol to ensure consistency. A think-aloud protocol was used in this experiment, which means that participants were encouraged to describe their thought process honestly and as detailed as possible. Limited information was provided to the participants in the model. The participants were able to request supplemental information, when they felt the available information was not adequate or sufficient for decision making. A recall-based method was used for knowledge elicitation, which requires the subjects to articulate their answers without any further information, as compared to the recognition-based method which requests the subjects to identify applicable items from a predefined list. Results from this experiment were used to augment the list of attributes extracted from literature and field studies. The final representation schema was presented to four other experts and was validated using a recognition-based method.

2.4 RESULTS

This section presents the results from each step and the representation schema for MEP coordination.

2.4.1 Literature review

Previous research provides three types of information that are relevant to MEP coordination, which were knowledge items, clash/interference types and solution classes. Table 1-3 shows 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. (2003) and Tabesh and Staub-French (2006). Korman et al. (2003) identified 13 knowledge items in their knowledge framework. Based on this framework, Tabesh and Staub-French (2006) 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. (2003) 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. With the purpose of having a comprehensive list of attributes for further investigation, a total of 25 knowledge items were included in the initial list.

Table 1: Knowledge items identified in previous research

Phase	Attribute	Explanation	Korman et al. (2003)	Tabesh & Staub-French (2006)
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		✓

Table 2: Clash types identified in previous research

	Clash type	Explanation	References
1	Hard clash;	physical interferences between components	Tabesh and Staub-French (2005); Staub-French and Khanzode (2007)
	Soft clash	interferences between design components and access spaces or violations of clearances	
2	Core clash;	core clashes must be resolved	Radke et al. (2009)
	Envelope clash	envelope clashes may under certain conditions be ignored if the designer determines that maintenance and other operational requirements will not be adversely affected	
3	Hard clash;	one building component physically yet unintentionally penetrating another building component	Tommelein and Gholami (2012)
	Soft clash;	components (subsystems) that are closer than a certain distance (a minimum clearance) from one another (e.g., distance in-between outer cylindrical surfaces of two pipes)	
	Time clash	spatial challenges (components potentially occupying the same space) anticipated when considering constructability or operability of the facility	
4	Actual;	actual (physical) interference occurs when two or more components physically interfere	Korman et al. (2003)
	Extended;	component interferes with extended space (such as access path for maintenance) that is associated with another component	
	Functional;	locations of components jeopardize the intended function of component	
	Temporal;	locations of components prevent proper construction sequencing and scheduling	
	Future;	locations of components do not allow future expansion of components and the respective systems	

Table 3: Solution classes identified in previous research

Attribute	Explanation	Korman (2003)	Tabesh & Staub-French (2006)
Detailing	modify detailed design of components, such as size, insulation, and support system	✓	✓
Layout	move components along their horizontal plane	✓	✓
Positioning	move components along their vertical plane	✓	✓
Application	alter design intent and performance of components	✓	
Scheduling/ Sequencing	adjust installation sequence and scheduling related attributes	✓	✓
Routing	Routing of uniform, linear components, such as piping, ductwork, and conduits;		✓
Validating	Validating the design assumptions, such as the necessity of a rainwater drain line in a specific location.		✓

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 (Tabesh and Staub-French 2005; Staub-French and Khanzode 2007). 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 (Tommelein and Gholami 2012). Radke et al. (2009) classified clashes into core and envelope clashes, according to the severity of clashes and whether resolution was needed. Korman et al. (2003) 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.

Table 3 summarizes the solution classes identified in previous research. Layout and positioning classes refer to moving components horizontally and vertically; detailing refers to modifying the detailed design of components; routing refers to routing of uniform and linear components; scheduling/sequencing refers to adjusting installation sequence; application refers to altering design intent; and validating refers to validating design assumptions. These seven solution classes were then tested in the field studies.

Previous research provides a good starting point for developing a knowledge representation schema for MEP coordination. Since the purpose of the representation schema is to capture and reuse MEP coordination knowledge, 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.

2.4.2 Field study

In the coordination meetings, one BIM coordinator and several specialty contractors were involved. Important information was exchanged and critical factors were discussed. Some information was documented by the BIM coordinator in the clash report or as viewpoint information in the coordination application. Viewpoint is a built-in function of the coordination application, which is a static 2D snapshot of part of the model with a viewpoint description in free text format and sometimes with additional comments or markups added to the snapshot. Both project teams used viewpoints with different levels of detail contained in the view point description. In Project A, the view point description usually included clash ID, system (clashing trade) and viewpoint number (e.g., "0114_ELEC-SLAB_01"). Project B included clash ID, system, level, zone, and open date. For example, in the viewpoint description "4_DUCT-ELEC_L02 ADMIN_B_10-04-2012", "4" represents the clash ID, "DUCT-ELEC" represents the clashing systems Mechanical duct and Electrical systems, "L02" means the clash was located on level 2, "ADMIN_B" refers to the specific zone/area that the clash was at, "10-04-2012" is the date when the clash was identified. Since the viewpoints are attached to the model, it is convenient in terms of communicate among the project team. However, the information contained in viewpoints is limited and very difficult to organize (current version does not support function such as search or filter). Due to these limitations, both projects had separate clash report prepared to include detailed information of the clashes and solutions. The clash report for Project A was in PDF format and contained information such as description of the clashes, responsible trade/person and solutions. The clash report for Project B was in Excel spreadsheet, which included categorized information such as clash ID, trades, level, zone, origin date, clash description, responsible person, resolution, due date, status and notes. Different projects may have different standards for clash documentation.

Nevertheless, currently documented information was mostly used for managerial purposes, which helped the project team communicate the clashing situation, monitor the progress and record as references. Currently documented information did not contain sufficient information for knowledge formalization and reuse. Some information was discussed in the coordination process but not properly documented. Table 4 shows the observation results from the two projects. The first column shows if the information is mainly used to describe the clash or the clashing object; the second column lists the information items discussed and/or documented for MEP coordination; column 3-6 shows whether the information was discussed or documented in the two projects; column 7 shows if the information is documented/discussed for management purpose; column 8 shows if the information represents coordination knowledge; and the last column indicates the possible sources to obtain the information. 29 information items were identified in the field studies, with 15 clash-based information items and 14 object-based ones. The most commonly documented information was clash ID, level, responsible trade, clash open date, and clashing systems.

The attributes identified in the literature are mostly object-based information and were sometimes discussed during coordination but not well documented. Some of object-related information is geometric information that can be extracted from the model, such as component geometry and slope; some can be represented as geometric information in the model if modeled properly, such as support system, insulation, clearance, installation space and access space; some can be represented in the model as proprietary information associated with model components, such as system, component type, material type and tolerance. Installation sequence can be linked with the model by integrating installation schedule with the federated model. Some other object-based information is usually not available in the model and needs to be included by the model authors, such as function of component/system. Some information is difficult to be explicitly represented, such as design or operation performance of component/system. Hence, attributes such as aesthetic, safety, productivity and performance were removed from the scope of this research. Safety, productivity and performance were considered in the representation schema as constraints needed to be considered for coordination, including spatial and non-spatial constraints. Except for clash type and solution, previous research did not provide structure to represent clash-based information.

Table 4: Information discussed and documented in the field studies

Information type	Information item	Project A		Project B		Management	Knowledge	Information Source
		Discussed	Documented	Discussed	Documented			
Clash-based information	Clash ID	✓	✓	✓	✓	✓		I
	Section	○	○	✓	✓	✓		M
	Level	✓	✓	✓	✓	✓		M
	Zone/area	○	○	✓	✓	✓		M
	Spatial relationship	○	○	○	○		✓	M
	Clash cause	○	○	○	○	✓	✓	I
	Clash type	○	○	○	○	✓	✓	I
	Clash severity	○	○	○	○	✓	✓	I
	Constraints	○	○	○	○	✓	✓	I
	Potential impacts	○	○	○	○	✓	✓	M/I
	Responsible trade	✓	○	✓	✓	✓	✓	I
	Solution	✓	○	✓	○	✓	✓	I
	Clash status	✓	○	✓	✓	✓		I
	Open date	○	✓	○	✓	✓		I
	Close date	○	○	○	✓	✓		I
	Due date	○	○	✓	✓	✓		I
Object-based information	System	✓	✓	✓	✓	✓	✓	M
	Component type	✓	○	✓	○	✓	✓	M
	Component geometry	○	✓	○	✓		✓	M
	Support system	○	○	○	○		✓	M/I
	Function	○		○			✓	I
	Material type	○	○	○	○		✓	M/I
	Insulation	○	○	○	○		✓	M/I
	Clearance	○	○	○	○		✓	M/I
	Slope	○	○	○	○		✓	M
	Performance	○		○			✓	I
	Installation space	○	○	○	○		✓	M/I
	Installation sequence	○		○			✓	I
	Tolerance	○		○			✓	M/I
	Access space	○	○	○	○		✓	M/I

✓: applied for all cases; ○: applied for partial cases; *blank*: not applied; I: input needed; M:can be obtained from model

During the coordination process, most of the documented information is clash-based information, mainly used for managerial purposes, but can also be captured to represent coordination knowledge. For example, clash cause, clash severity, constraints, responsible trade, solution were documented for management purposes but also include technical and experiential coordination knowledge from the experts. Information documented mainly for management purposes include clash ID, section, level, zone/area, clash status, open date, close date and due date. It is important to consider the current work practice when developing a knowledge representation schema, because it is more likely to be adopted if it can be incorporated into existing work processes. Figure 4 shows the list of attributes that combines the findings from literature and field studies, containing 35 information items. These information items were tested in a laboratory experiment, described subsequently.

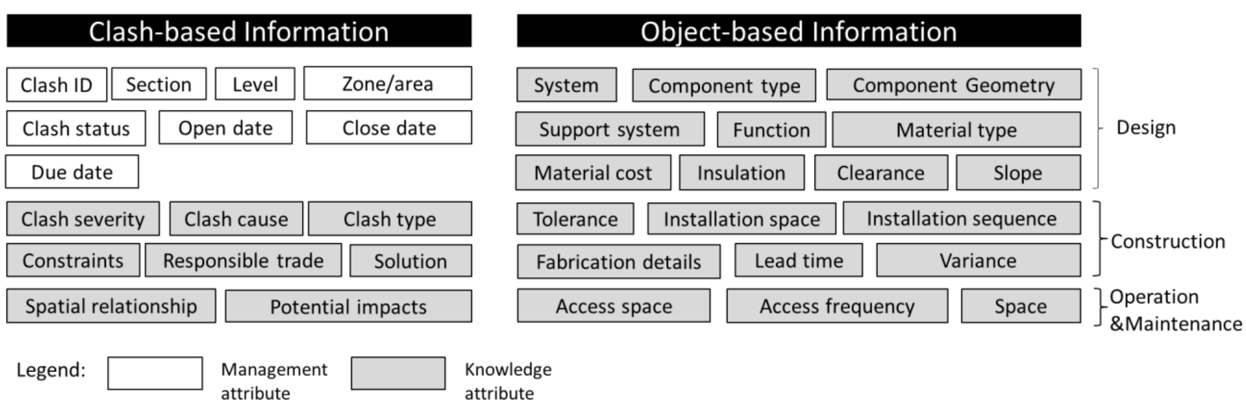

Figure 4: Attributes identified from literature and field studies

2.4.3 Laboratory experiment

During the experiment, participants controlled the model and verbalized what they were doing, what information they were considering, what additional information they needed and what information they would document. Figure 5 shows individual and cumulative counts of information items used by the 6 subjects. The cumulative count is the count of unique information items identified by the subjects. After the fourth subject, the cumulative count reached a diminishing return trend, which indicates that no further information items were likely to be identified even if additional subjects were involved. Thirty unique attributes were cited by the subjects.

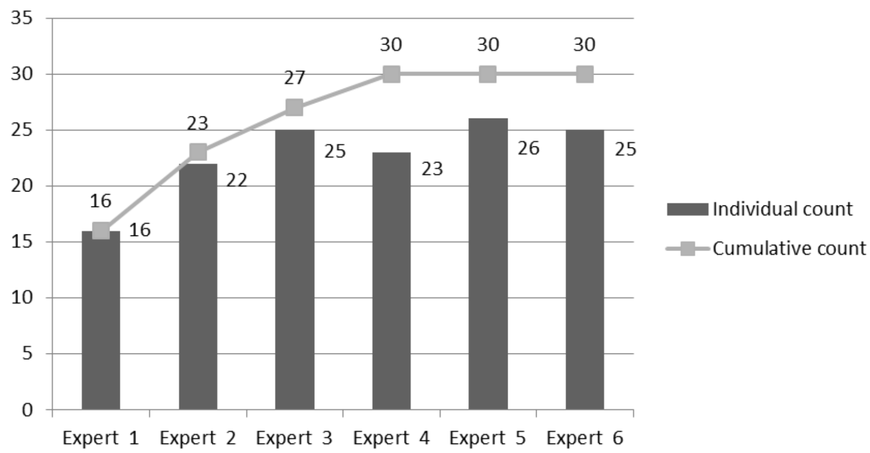

Figure 5: Individual and cumulative counts of information items used by 6 subjects

The subjects tended to start with information available from the model, such as what systems the clashing objects belong to, the object type, how much the objects are clashing (e.g., barely clipping or penetrating through), if it is a hard clash or soft clash (e.g., clashing with clearance space), if the object is flexible or rigid (e.g., flexible transition duct), if a critical component is involved (e.g., variable air volume box), if there is a required slope and whether insulation was modeled. After extracting information about the clashing objects, the subjects tended to investigate the context by extracting information about the location of the clash (e.g., whether it is in a mechanical room or not), the overall layout of the system, any constraints related to the clash (e.g., the location of the junction box if conduits were clashing with other objects), if there are more clashes along the run, and the available space for movement. Some subjects tried to analyze the design intent by investigating the context. Based on this information, they usually provided an assessment on the possible clash cause (e.g., design issue or modeling issue) and clash severity. Additional information requested by the subjects include the general pre-defined priority sequence of the systems (usually determined before coordination), maintenance requirements, installation sequence, and the possibility of reshaping the system without influencing its designed function. The results from the experiment clarified the thought processes of the experts when performing coordination tasks and the information items involved during the processes.

2.4.4 Representation schema

Based on the findings from the literature, field study and laboratory experiment, a representation schema was developed for MEP coordination (as shown in Figure 6). This schema integrates knowledge items related to coordinating MEP systems (e.g., clash description, clash context, and clash evaluation) as well as managing the coordination process (e.g., clash management). It includes object-based information and clash-based information. The four categories represent the general thought process of experts during design coordination, which are clash description, clash context, clash evaluation and clash management.

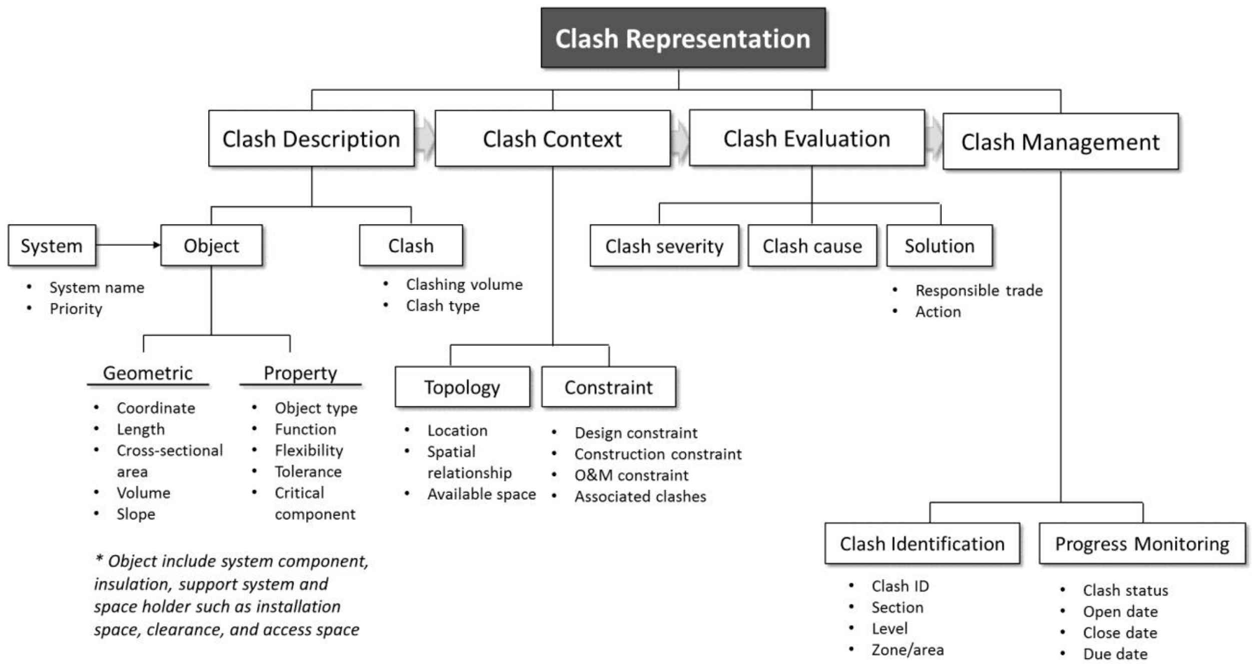

Figure 6: MEP coordination representation schema

The clash description category includes information used to describe the objects that are clashing and associated interference. In this category, object-based information includes the belonged system of the object, geometric information (e.g., coordinates, length, cross-sectional area, volume and slope) and property information (e.g., object type, function, flexibility, tolerance, critical component). Critical component represents architecturally important elements, such as sprinkler heads, J-box, VAV box. Object-based information can be extracted from the model directly or indirectly. Support systems, installation space, clearance and access spaces that are included in the knowledge framework developed by previous researchers (Korman et al. 2003, Tabesh and Staub-French 2006) are possible to be modeled as objects or space holders in the coordination model. Clash-based information used for clash description is clashing volume and clash type (e.g., hard and soft clash), based on the types of objects that are clashing.

The next category represents the process of analyzing the clash context. Two sub-categories are topological context and constraints. Topological attributes can be used to describe the location of a clash, spatial relationship between the clash and the surrounding objects and the available space for adjustment. Constraints include performance or functional constraints in design (e.g., code requirements), construction (e.g., installation requirements such as tolerance, and lead time), and operation and maintenance (e.g., maintenance requirements such as access path). Another type of constraint represents the situation when one object is clashing with multiple objects at different location. This information needs to be taken into consideration when analyzing the clash context and clash severity. It is possible to obtain topology information from the model; however, constraint information usually needs input from multiple stakeholders.

Clash evaluation contains information that requires input from the coordination team, which includes clash severity, cause of clash (e.g., non-issue, design issues and modeling issues), and solution to resolve the clash. Solution specifies the responsible trade for a clash and any actions needed. Responsible trade includes the companies (e.g., general contractor, mechanical, electrical, or fire protection subcontractors) or individuals that are responsible for the assignment. Examples of action items include rerouting the electrical conduits, flattening the duct, creating an RFI, or requesting information from facility maintenance group. This category captures factors that experts considered when evaluating the clash situation and reaching a satisficing (Simon 1969) solution.

Clash management contains information that is used to track the clash status. Typical information within this category includes information used to identify a clash (e.g., clash ID, section, level and zone/area) and to monitor the coordination process such as clash status (e.g., new, active, and resolved), the start, close and due date of a clash. Current mainstream coordination applications already support documentation of clash management information.

With this representation schema (Figure 6), basic knowledge for spatial conflict coordination in MEP systems can be captured. This schema can be integrated into the current coordination practice to formalize the documentation process and increase the information that can be captured.

2.5 VALIDATION

Since the purpose of developing this representation schema was to provide a formalized structure to capture experiential knowledge during the coordination process, such schema needs to be comprehensive enough to cover important knowledge attributes and flexible enough to accommodate different project settings and preferences. Five one-to-one expert evaluation interviews were conducted in order to assess the comprehensiveness and flexibility of the proposed schema. Comprehensiveness was measured by precision and recall. Flexibility was evaluated by including with five subject domain experts from different companies to account for diversity. Table 5 summarizes the types of organizations that the subjects employed at, roles in organization, and years of experience in the current role. The subjects that participated in the validation test were different than the ones involved in the laboratory experiment.

Table 5: Profiles of the subject domain experts

Subject expert	Types of organizations employed at	Roles in organization	Years of experience
1	General contractor	BIM engineer	5
2	General contractor	Virtual Design and Construction (VDC) manager	4
3	General contractor	BIM coordinator	2.5
4	MEP consulting	BIM specialist	5
5	Mechanical contractor	Detailing manager	11

The representation schema (Figure 6) was validated by the subject domain experts using a recognition-based method. Different than the recall-based method, the subjects were provided with a list of attributes (including the attributes in the schema and additional attributes intentionally included) and asked to identify the ones that were correct and important. In general, three steps were taken, which included schema introduction, attribute evaluation and follow-up questions. First, the subjects were briefed about the purpose of this study, the sources of gathering different concepts and data, and how they were structured to form hierarchies. After the subjects had general understanding of the schema, the attributes under each category was defined and explained respectively. Two questions were asked to help the subjects assess the correctness of each attribute: 1) Is this one of the factors that you would consider when resolving a clash? 2) If you want to reference back the decisions you made in the past on certain clashes, what information would you want to check? After evaluating the correctness, the subjects were asked to identify the most important attributes and name additional attributes that were missing from the list. Follow-up questions were asked regarding the current practice of documentation in MEP coordination, the representativeness of the thought flow reflected in the schema, the ease of use for locating concepts and attributes in the schema, and the subjects' perception of incorporating such schema for clash management.

The number of attributes referenced by the subjects was counted and compared to the number of attributes in the proposed schema to calculate the precision and recall rate using the following formulas (Rijsbergen 1979):

$$\text{Precision} = \frac{\text{referenced attributes} \cap \text{proposed attribute}}{\text{proposed attribute}}$$

$$\text{Recall} = \frac{\text{referenced attributes} \cap \text{proposed attribute}}{\text{referenced attributes}}$$

The average counts of five subjects were used as the counts of referenced attributes. Table 6 shows the results of precision and recall for the four categories in the schema. It is shown that the overall all precision and recall rate of this schema are 0.93 and 1.00, which means that the proposed schema were considered accurate and no significant attributes were found missing.

Table 6: Validation results

Category	Clash Description	Clash context	Clash Evaluation	Clash Management	Overall
Precision	12.4/14 = 88.6	6.6/7 = 0.94	3.8/4 = 0.95	7.8/8 = 0.98	30.6/33 = 0.93
Recall	12.4/12.4 = 1.00	6.6/6.6 = 1.00	3.8/3.8 = 1.00	7.8/7.8=1.00	30.6/30.6 = 1.00
Important attributes	System name, priority, object type, slope, critical component, clash type	Location, spatial relationship, operational and maintenance constraint, associated space	Clash severity, responsible trade, action	Clash status, due date	

In the clash description category, the most important attributes identified by the subjects were system name, priority sequence of the coordinated systems, object type, critical component and clash type. Although the subjects mentioned that various attributes may be considered for different systems and objects, the abovementioned features are always important to consider. In current practice, all the listed geometric information is available in the model. However, in property attributes, only the object type can be found in the model. Other attributes can be associated with model elements, but are not currently included. Different project teams use different naming conventions for object type and different classification systems for clash type (e.g., one company used “hard clash – barely touching – clearance clash”, while other companies used “hard clash and soft/clearance clash”). This was also observed in validation of attributes in other categories (e.g., design constraints, clash severity, clash cause). The level of detail of the proposed schema allows different classification to be incorporated according the customized settings of each organization. Nevertheless, a standardized classification system is needed to enable cross-organizational integration.

In the clash context category, topological attributes can be gathered from the model, while the constraint attribute are usually implicitly considered or informally discussed. Only the clearance space required by operational and maintenance practices was explicitly modeled.

In the clash evaluation category, all five subjects considered clash severity during coordination, but only one subject documented this information. The main challenge for formally documenting such information was time pressure. Within a limited time frame, only information in the clash management category is documented or partially documented.

The proposed representation schema was then examined fit into current work practices at each organization. Although different classification systems and documentation formats were used in different organizations or projects, the sources of the attributes in the schema can be easily identified and the structure can be applied and incorporated into current documentation templates. After a short explanation, the subjects became aware of the representation schema and could locate concepts and attributes easily without external assistance. All subjects expressed willingness to implement such schema in their projects when the application is made available.

The validation results demonstrated the comprehensiveness of the formalized representation schema. Because of the designed structure, this representation schema can be expanded by including additional information items under the related category.

2.6 Conclusions

This chapter presents a formalized representation schema for MEP coordination that supports representing and capturing information that embodies experiential knowledge and reflects coordination practice. This schema presents factors that are considered for clash analysis, resolution and management. It is envisioned that information captured using this schema can provide structured data for further analysis and can be used for knowledge formalization and reuse in MEP coordination. The clash management information can be used to analyze the coordination performance and productivity. Analysis can be performed using the performance data and associated clash features. Multiple sources (i.e., literature, field studies and laboratory experiment) were used for this study to ensure the comprehensiveness and practicability of this schema. Compared to the previously developed knowledge framework, this representation schema provides a structure that can represent knowledge-related information more explicitly and can be more easily integrated into current work practice. This chapter also discusses what are the possible information sources and how can this information be represented in a model-based environment.

This knowledge representation schema was developed based on findings from literature review, two field studies and laboratory experiments with six experts. The expert validation showed that the schema was comprehensive to represent information items considered and used for MEP coordination. Because of the various project settings and preferences, it is very challenging to have a single standard specification for all the information contained in the schema. The level of detail currently contained in this schema is robust and can be adjusted or extended when implemented. Future work includes developing a model-based knowledge capture tool to implement this representation schema.

Chapter 3 Process Knowledge Capture in BIM-Based Mechanical, Electrical, Plumbing (MEP) Design Coordination

This chapter will answer research question 2: How to capture process knowledge in BIM-based MEP design coordination with information technology support. Research Question 1 provided a knowledge representation schema for Mechanical, Electrical and Plumbing (MEP) design coordination. Subsequential to Research Questions 1, Research Question 2 focuses on the knowledge capture and formalization during BIM-based MEP design coordination. A prototype system was designed for model-based knowledge capture and tested in a construction project. The proposed system described in this chapter indicates that process information can be captured and represented with direct links to the model, enabling model-based knowledge capture and further analysis of process information.

3.1 INTRODUCTION

In recent years, the utilization of computer-aided information and communication technologies such as Building Information Modeling (BIM) has become a prevailing trend in the Architecture, Engineering and Construction (AEC) industry. The data-richness nature of BIM enables creating, storing, processing and representing parametric information as well as establishing connections between model components and related information. Researchers have discussed BIM strengths in managing the product information, but little is discussed regarding capturing and representing process information in a computer-interpretable manner, such as information related to clashes and solutions in model-based design coordination. Documentation of this process information, if any, is usually conducted in the form of text, paper drawings with markups or digital snapshots of model components with markups. While product information is well represented in 3D models, process information representation remains in 2D. Design coordination is typically conducted in a model-based environment, but since no linkage is established between review markups and model components, the knowledge and information generated during the design coordination process is difficult to be used in further model-based analysis.

Design coordination is an iterative process and can be considered as a source for gathering data and formalizing construction knowledge (Wang and Leite 2012). The information generated in the design review process, if documented properly, can be utilized as a basis for construction knowledge formalization and reuse. However, it has been observed that information generated during the design coordination process was either not documented or not properly documented (Tommelein and Gholami 2012; Wang and Leite 2012). In most cases, the BIM engineer posed an issue and the construction team came up with a solution, which would be represented in an updated model. As long as the clashes were resolved, what changes were made and why those changes were made were not the questions valued by the construction team. Many changes were only represented in an updated model and reside in the minds of associated participants. If knowledge is not formalized, it is difficult to learn from it. Process information and experiential knowledge is often lost due to inadequate and unstructured documentation. Furthermore, since there is no standardized process and systematic structure to capture clash-relevant information, managing and organizing clashes is usually tedious and inefficient.

This research question aims at developing a model-based knowledge capture system to formalize experiential and process knowledge for design coordination. This study focuses on MEP design coordination at the stage of preconstruction, after construction documents are substantially complete and before fabrication drawings are issued. During this coordination process, experiential and process knowledge regarding the location of multiple systems, discussion of the potential conflicts, and resolution to the identified clashes, is frequently exchanged and reutilized. The envisioned model-based knowledge capture system not only enables efficient management of process information with advanced model-based tag functions but also serves as a basis for semi-automated construction knowledge extraction and formalization. A prototype system was developed and used to demonstrate the feasibility and advantages of this approach.

3.2 LITERATURE REVIEW

Knowledge capture (KC) is a common approach to formalize and transfer knowledge (Tan et al. 2009). There are various techniques and technologies for knowledge capturing (Al-Ghassani 2002). Some are supported by information technologies (IT). This section provides an overview of the KC approach and its adoption in the AEC industry, and discusses promising KC methods for knowledge formalization in model-based design coordination.

3.2.1 Knowledge capture techniques

Various technologies and approaches were implemented for knowledge capture, which include, but are not limited to, expert interviews, direct observation (action protocol), concept mapping, brainstorming, consensus decision making, nominal group technique, repertory grid, and Delphi method.

Expert interviews aim to produce a record of the knowledge and are commonly used in the early stages of tacit knowledge capture (Lindlof and Taylor 2011). Interviews of subject matter experts can help transform tacit knowledge of an individual into more explicit forms. Interview types include unstructured, semi-structured and structured interviews. The general concept of an interview in regards to knowledge capture is not constrained to one-to-one expert interview. It also applies in expert workshops or focus groups. Reliable knowledge capture depends on multiple factors, including the interviewee's ability to articulate tacit knowledge, the interviewer's ability to understand and interpret expert's verbal description correctly and precisely, interview skills, communication problems and interview settings. Expert interviews can be very expensive to conduct in terms of time and resources required for information gathering and processing.

Observational techniques are another widely applied means of capturing knowledge. Observation without interruption is best used to capture the spontaneous nature of a particular process or procedure. This approach is most useful in behavioral analysis (Awad and Ghaziri 2007). However, it is difficult to extract the reasoning and thoughts behind the behaviors observed. Another source of errors comes from the fact that people may act differently when they know they are under observation.

Protocol Analysis uses a think-aloud approach, in which experts verbalize their thoughts and considerations while going through a task. The investigator does not interfere in the problem solving process. Protocols are recorded and analyzed afterwards. This approach is similar to observational approach, but addresses the limitation of extracting implicit reasoning behind the behaviors, to some extent (Ericsson and Simon 1985; Awad and Ghaziri 2007).

Concept mapping is a diagrammatic way of representing knowledge in a particular knowledge domain, which uses nodes to represent concepts and arrows to label the relationship between them. This is an effective approach to represent complex structure and communicate ideas (Leake et al. 2003; Marshall et al. 2006; Awad and Ghaziri 2007).

Repertory grid technique is used to represent experts' reasoning about a particular problem in a table-based format. It can be difficult to manage when the size of grid is large with complex details. This approach is commonly used in the early stages of knowledge capture (Liou 1992; Bradshaw et al. 1993; Moynihan 2002; Neve 2003; Award and Ghaziri 2007).

All the above KC techniques can be supported by Information and Communication Technology (ICT). Recently, KC approaches that are more IT-intensive have been applied, which include database technologies, web-based knowledge documentation and sharing (Eockwell et al. 2008; Gracia and Stoffel 2008), knowledge-based systems (KBS) (Dhaliwal and Benbasat 1996; Laudon and Laudon 2011) and annotation technology (Li et al. 2010). In the product engineering domain, a large amount of product information is described through design documents, however, tacit knowledge are implicit within these documents (Li et al. 2008) or in other contexts. Eliciting and extracting this information is essential to achieve success in the product development process (Cao et al. 2010). A survey conducted by Heisig et al. (2010) pointed out the need for retrieval of previous designs as well as the need to capture knowledge and information from current designs to support future engineering tasks.

3.2.2 Knowledge capture in the AEC industry

In the AEC industry, the importance of knowledge management (KM) has been increasingly recognized. A survey conducted in 2003 showed that about 40% of the responding construction organizations already had a KM strategy with another 41% planned to have a strategy within a year, and about 80% perceived potential benefits of implementing their KM strategy (Carrillo et al. 2003). There are some particular challenges of KM implementation in the AEC industry. Firstly, most construction knowledge is tacit, which resides in the minds of domain experts (Khalfan et al. 2002). There is a lack of organized processes to capture lessons learned and disseminate useful knowledge to other projects (Khalfan et al. 2002). Secondly, in the AEC industry, there is a strong reliance on informal networks and collaboration and 'know-who' to locate the repository of knowledge (Kamara et al. 2002). There is a strong reliance on the knowledge accumulated by individuals but no formal way of capturing and reusing much of this knowledge (Kamara et al. 2002). Thirdly, because of the result-driven nature of the industry and the considerable pressure on time and cost, practitioners are often reluctant to spend extra time and effort for KM and KC. Post project reviews (PPRs) are usually the means for capturing lessons learned from projects (Kamara et al. 2002). Carrillo et al. (2004) summarized the barriers of KM implementation in construction as lack of standard work processes, not enough time, organizational culture, not enough money, employee resistance and poor IT infrastructure. There is difficulty in tracking the people involved in a decision making process and revealing the intent behind decisions made. Post project reviews (PPRs) are usually the means for capturing lessons learned from projects (Kamara et al. 2002). In addition to extra effort entailed, the accuracy and completeness of captured knowledge is weakened due to time gap between execution and documentation.

Karmara et al. (2003) contended that in order to overcome the limitations in current industry practice on knowledge capture and reuse, it is necessary that process information and knowledge is captured 'live' while the project is being executed and presented in a format that will facilitate its reuse both during and after the project. Hartmann (2008) also concurred that successful KC technology adoption needs to suite existing work practices. Nowadays, the emergence of 3D parametric modeling techniques enables capturing and representing knowledge in a model-based system. The fundamental challenge is to make the various virtual construction elements self-aware in the context of other virtual construction elements, elements of design solutions, and other lifecycle concerns (Fischer 2006). Construction knowledge has been formalized using model-based systems in several sub-domains, e.g., steel construction (Anumba et al. 2000), rebar constructability (Navon et al. 2000), and reinforced concrete structure (Fischer 1993; Fischer and Tatum 1997) and workspace generation (Akinci et al. 2002). The knowledge capture approach commonly used in their research is case study or expert interviews, which is also a form of PPRs, thus expensive to apply on a large scale and has the limitations of PPRs as discussed above. Researchers (Reiner and Fruchter 2000) proposed 'live' capture and reuse of project knowledge in design evolution stage. The need for capturing construction knowledge 'live' has not been adequately addressed.

In MEP design coordination, issues and conflicts are frequently identified but the process information for conflict resolution is not properly documented to facilitate knowledge capture and reuse. During BIM coordination, there is little time available to characterize clashes or to document the causes of clashes due to time pressure (Tommelein and Gholami 2012) and the lack of efficient documentation tool. In current practice, clash-relevant information is typically typed in by the coordinator in the design coordination application or in a separate documents (e.g., clash report or meeting minutes). When developing KC system for design coordination, it is important to consider the current work practice and constraints.

In summary, construction knowledge has been historically provided in various forms including formal means such as specifications, work procedures, construction codes, task sequences and informal forms such as verbal suggestions, experience-driven decision-making and evidence from on-site execution. Formal knowledge representations are currently mainly paper-based documents and process knowledge is seldom properly documented. Such scattered and implicit representation of knowledge makes it difficult for knowledge formalization, transformation and reuse. As computer-based solutions are gradually replacing paper-based processes, information documentation protocols are also greatly altered. The KC system for design coordination needs to fit into current work practice without adding too much burden during implementation.

3.3 Research Approach

This research was conducted in three phases: requirements elicitation, system design and prototype demonstration.

As discussed in the literature review, a knowledge capture system should not only take into consideration of knowledge management (KM) requirements, but also the condition and requirements of current work practices. Therefore, requirements elicitation in this research consists of two parts: KM requirements and coordination requirements. KM requirements entail that the system provide sufficient functions to capture the categorized information in the knowledge representation schema developed in Research Question 1. KM requirements are based on the data type, availability and sources of the identified features in the design coordination knowledge schema. Coordination requirements entail that the system support the accomplishment of coordination tasks. Knowledge elicitation of coordination requirements are based on expert interviews and protocol analysis.

Based on the specified requirements, a model-based knowledge capture system with the desired functions was designed and prototyped as a plugin of a widely used model-based design coordination application, Autodesk Navisworks Manage 2013. The plugin was developed using Visual Studio C# 2013. The graphical user interface (GUI) was designed under .NET 3.5 Framework. The .NET APIs of Autodesk Navisworks

Manage 2013 were used to implement most functions relevant to connecting models with process information generated during design coordination.

The prototype system was demonstrated on Windows 7 operating system on personal computers (with 1.60-2.7GHz processor and 4-8 GB RAM) in a retrospective test case using design coordination data gathered from a construction project of a rental car facility in the United States. The prototype system was also demonstrated on the high-resolution touch screen system, Lasso, developed at the Texas Advance Computing Center (TACC)'s Visualization Laboratory. Lasso is a touch-sensitive tiled display that consists of six 46" monitors in a 2x3 grid configuration at a resolution of 12.4 megapixels (5760x2160) and supports human-computer interaction utilizing a PQ Labs' 32-point multi-touch infrared perimeter and a Microsoft Kinect (Westing et al. 2011).

3.4 RESULTS

This research aims at exploring the feasibility and potential of capturing information generated during the design coordination process and representing such information in a computer-interpretable manner. The developed prototype system is called "TagPlus". This section presents the results on the system development which includes requirements elicitation, system design and prototype demonstration.

3.4.1 Requirement elicitation

Table 7 shows the data requirements from the knowledge management perspective. There are two types of association: clash-based and object-based. Clash-based information is associated with a clash which has a group of clashing objects (as shown in Figure 7). Each clashing object has its own set of object information. One object can also have multiple clash tags associated with it. For example, the conduit in Figure 7 might be also clashing with a plumbing pipe in its run.

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Table 7: Data representation requirements from the KM schema

Schema		Data Type	Association	Data Source
Clash Description	System	String	Object	User input
	Cross-sectional area	String	Object	Model
	Volume	Integer	Object	Model
	Slope	String	Object	Model
	Object_type	String	Object	User input
	Function	String	Object	User input
	Critical component	Boolean	Object	User input
	Clashing volume	Double	Clash	Model
	Clash type	String	Clash	User input
Clash Context	Location	String	Clash	Model
	Spatial relationship	String	Clash	Model
	Available space	String	Clash	Model
	Design constraint	String	Clash	User input
	Construction constraint	String	Clash	User input
	Operation & maintenance constraint	String	Clash	User input
	Associated clashes	Integer	Clash	Model
Clash Evaluation	Clash_Severity	String	Clash	User input
	Clash_Cause	String	Clash	User input
	Responsible_trade	String	Clash	User input
	Action	String	Clash	User input
Clash Management	Clash_ID	String	Clash	User input
	Section	String	Clash	Model
	Level	Integer	Clash	Model
	Area/Zone	String	Clash	Model
	Clash_Status	String	Clash	User input
	Open_Date	Date	Clash	User input
	Close_Date	Date	Clash	User input
	Due_Date	Date	Clash	User input

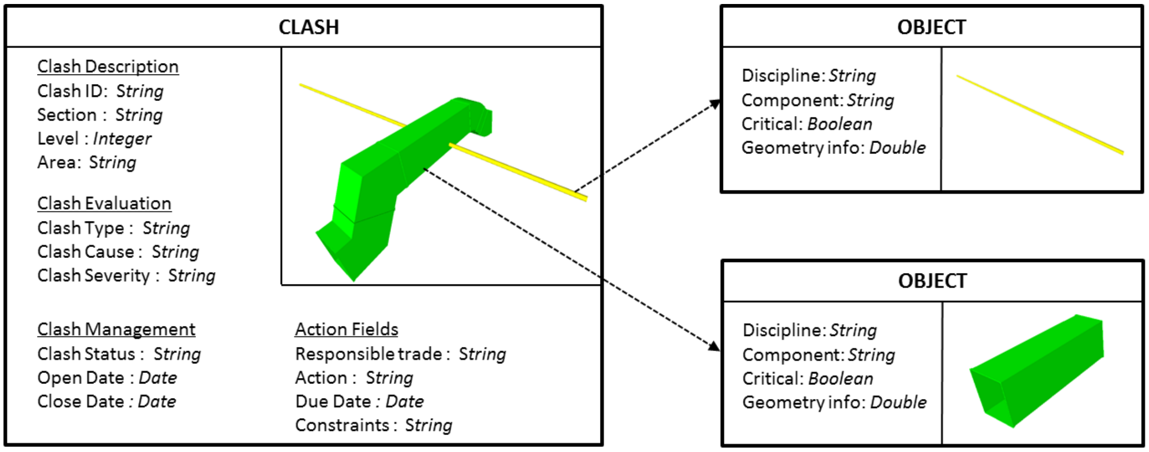


Figure 7: Clash properties and object properties

In the clash properties, four types of information will be documented: clash description, clash evaluation, clash management and action items. Clash description section include basic information used to describe a clashing situation, which include clash ID, section, area, level; clash evaluation information include clash type, clash cause, clash severity; clash management information include clash status, open date and close date; action items represent the solution or steps of solution to resolve a clash. Relevant data includes responsible trade, action taken, due date and constraints. One tag can contain more than one action item which documents the series of action used to resolve a clash.

In the object properties table, information of a specific model element is captured, which includes the discipline it belongs to, the component type, whether it is a critical component and the geometry information. Table 8-12 shows definitions of each data item.

Table 8: Definitions of clash type

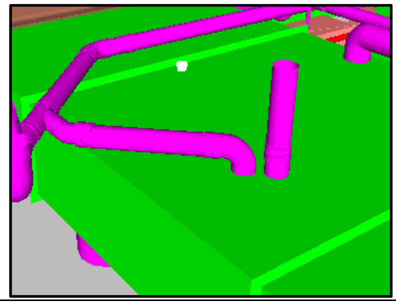
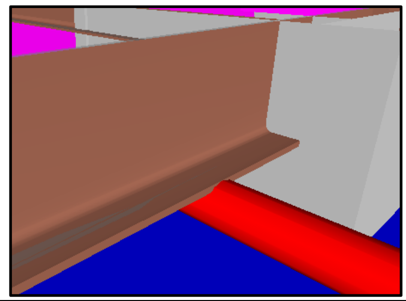
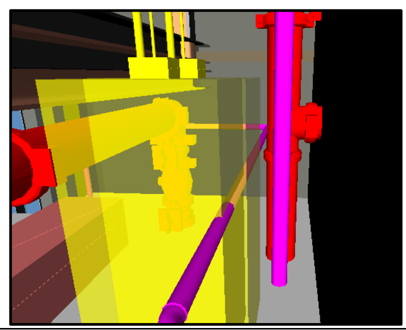
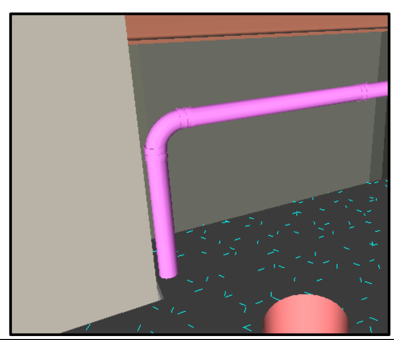
Clash Type	Definition	Example
Hard Clash	physically conflicting and the clashing depth (the vertical distance from the clashing point to the clashing surface) is more than 2 inches	
Barely Clipping	physically conflicting and the clashing depth (the vertical distance from the clashing point to the clashing surface) is no more than 2 inches	
Clearance	object conflicting with equipment access clearance	
Soft Clash	not physically conflicting, but modification is needed (e.g. tolerance, installation requirements and design requirements)	

Table 9: Definitions of clash cause

Clash Cause	Definition
Design issue	The clash is caused by design errors or omissions and cannot be resolved within the construction team. RFIs need to be issued to the design team.
Construction coordination issue	The clash is caused by inadequate coordination among construction trades and needs to involve multiple subcontractors to resolve the clash.
Modeling error	The clash is caused by modeling errors of the subcontractors and can be resolved within the construction team

Table 10: Definitions of clash severity

Clash Severity	Definition
High	This clash will lead to cost overruns and schedule delays and needs to be resolved as soon as possible (e.g., on critical path of the schedule, multiple trades involved, large/critical equipment, architectural significant spaces etc.)
Medium	This clash will have impacts on cost and schedule and needs to be resolved before construction execution, but is not on critical path or requires further information.
Low	This clash will have minimum impacts on cost and schedule and only requires field adjustment or verification.

Table 11: Definitions of clash status

Clash Status	Definition
Active	The clash is caused by design errors or omissions and cannot be resolved within the construction team. RFIs need to be issued to the design team.
Hold	This clash needs to be resolved after other issues have been resolved
Resolved	This clash has been resolved
Ignored	This clash can be ignored and does not need any movement

Table 12: Definitions of object property

Object Property	Definition	Example
Discipline	The responsible trade	Mechanical, Electrical, Plumbing and Fire Protection
Component	The component type	Domestic cold water, sanitary pipe, variable air volume (VAV) box
Critical	This component has absolute higher priority not to move	VAV box, fire sprinkler heads
Geometry information	The information that describes the geometry of a model element	Area, length, elevation, slope

In addition to KM requirements, the coordination requirements were elicited from expert interviews. Based on the results of expert interviews, preferable functions include basic tag functions such as creating, saving, editing and deleting tags, as well as more advanced functions such as establishing links between tags and associated model components, semantic search of tags or comments, grouping tags with certain hierarchies and exporting tag information for future use. These functional requirements are described using Use Cases, which are used to identify the major tasks performed by users of a system (Wiegers 2003). In other words, Use Cases show how a system will/can be used. The Use Case Diagram (Figure 8) illustrates the basic functions that the system supports. In Unified Modeling Language (UML), actors are parties outside the system that interact with the system, represented as a stick figure in a Use Case Diagram. A use case is a high-level description of an activity that will be performed on a system, represented by an oval with the name of the use case inside. A sequence of individual steps, also known as a flow of events, may be required for a use case. One use case may involve several different sequences of steps, which are referred as scenarios. Connecting lines between actors and use cases show which actors participate in a certain use case. In "TagPlus", the process information generated during design review is captured and represented with "tags" that can be directly linked to specific model elements. The primary actors involved are specified as a user (the one who uses the "TagPlus" system, usually a BIM coordinator), tag library (the data structure that stores all tag information), and model that is under review.

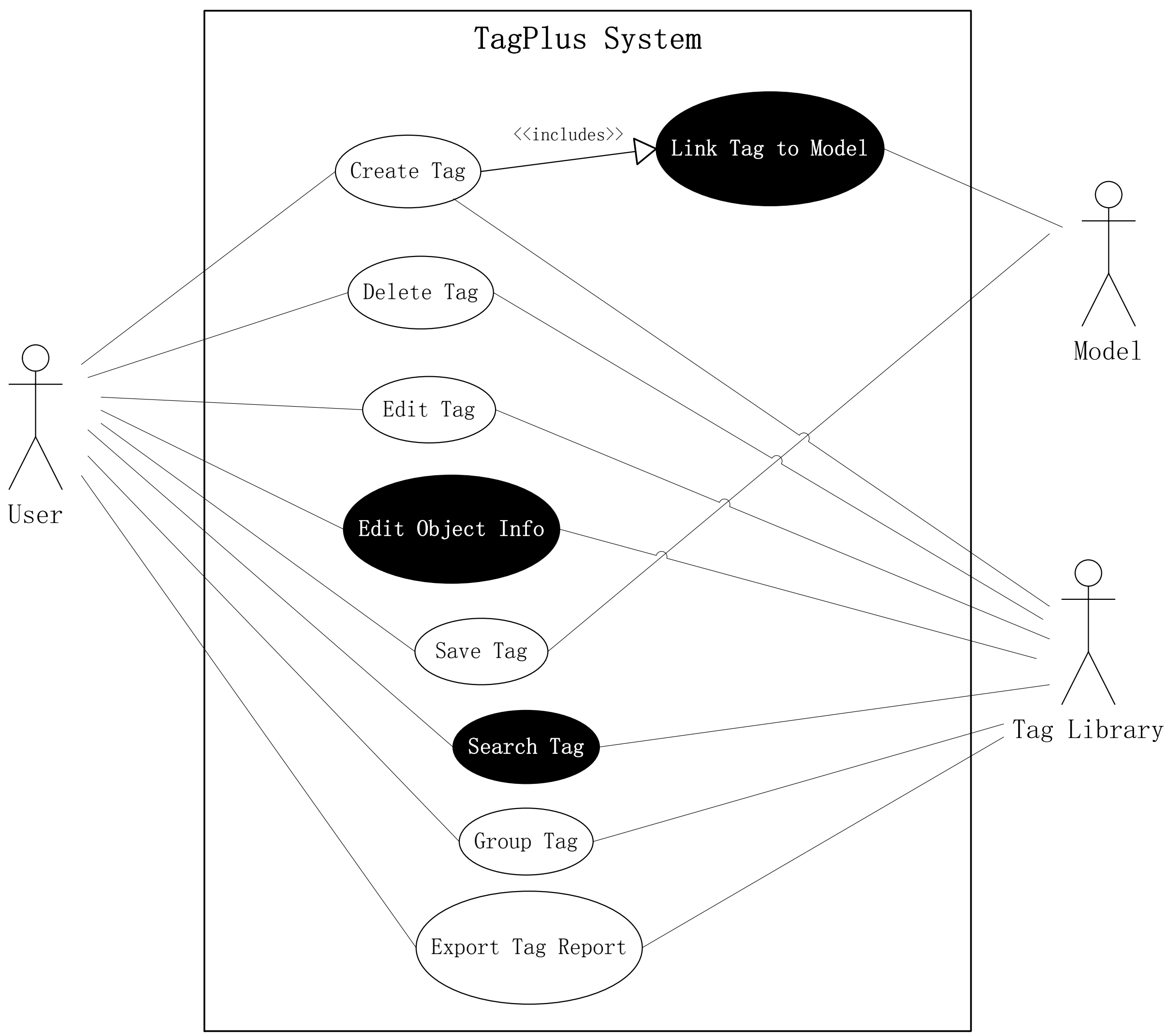


Figure 8: Use case diagram for the "TagPlus" system

Except for the basic coordination requirements, the proposed system stores coordination information as categorized data which can be searched, grouped and exported for further analysis. The highlighted use cases are new functions as compared to the conventional tagging systems. Some of the main use cases shown in Figure 2 are described as follows.

Create Tag: When there is a discussion or decision needs to be made regarding certain parts of the model, a tag can be created. The user needs to input information such as clash ID, section, level and action items; clash type, cause, severity and status can be selected from the predefined dropdown list which can be edited as needed; the date when a tag is created is automatically documented but also can be changed; the interrelation between the tag and the model elements is specified by the user by selecting certain piece(s) of the model when creating the tag. This information is automatically saved when a tag is created.

Edit Object Information: Due to various modeling standards and requirement, the information of a particular model component might be insufficient for KM and coordination. To overcome this challenge, the proposed system provides functions to edit and add object data, as well as extract geometry information from the model.

Search Tag: The user may search for clashes by clash ID, open date, responsible trades, or even by specific model elements. When the matching tags are found, they will be listed in the "Viewer" window.

Group Tag: For the convenience of the users when organizing the tags, the grouping function is provided so that the user can merge several tags into one folder or combining several folders into a folder with higher hierarchy.

Export Tag Report: In addition to saving tag information as part of the model, this information can also be exported and saved in other formats such as CSV. Such external information storage may ease future manipulation or utilization of the data.

3.4.2 System design

The plugin's GUI is designed within .NET 3.5 Framework. The Windows Form class of .NET is the basic framework of the GUI, and all other sub window and menu list are created using build-in objects from .NET library System. As is shown in Figure 9, the plugin user interface is composed of three main components: Main Form, Tag Property Form, and Object Property Form. The main menu offers operations like saving tags, searching tags, and editing tags. Tag property form is the most used part since all important tag operations are found here. Users can create new tags, save and delete existing tags, and select a certain tag to review the tag information and have the associated assemblies highlighted in the model. The Object property form presents object information needed for coordination, such as discipline, component type and geometry information.

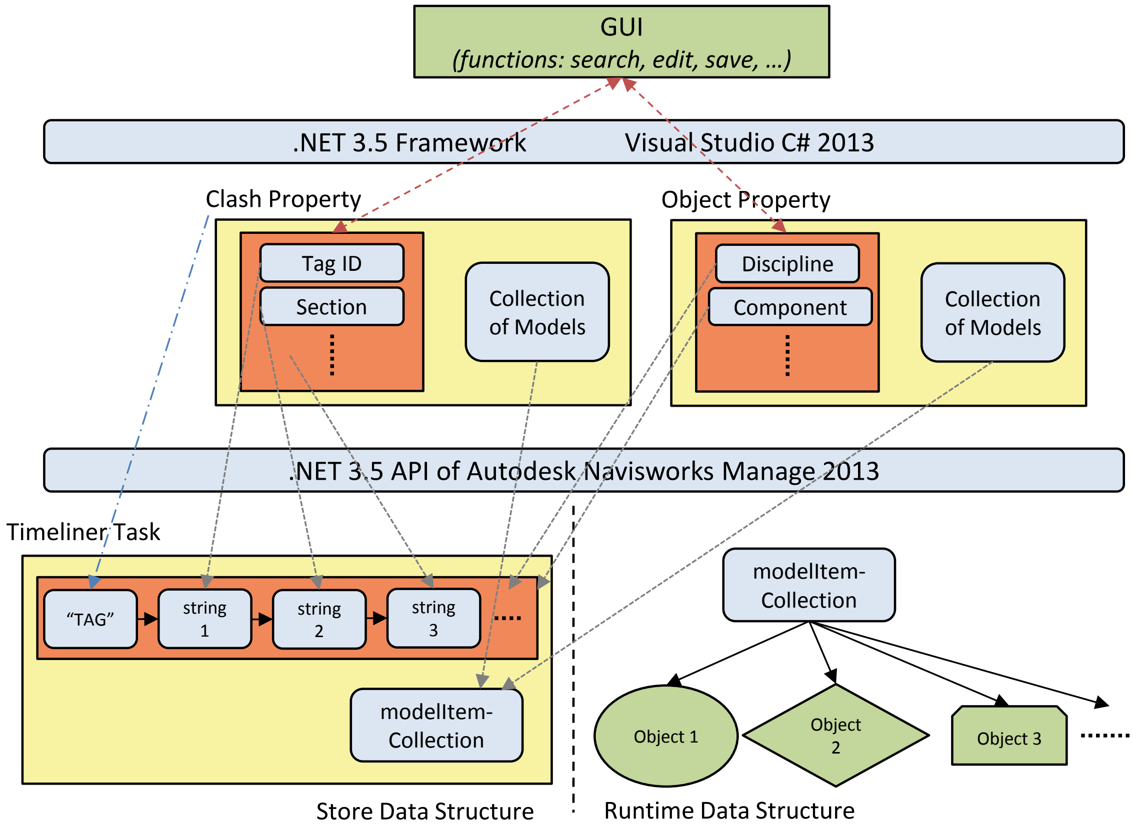


Figure 9: Software architecture of the prototype system

A C# data structure tag was designed as the data structure to store all tag-related information. Its data members include data types like strings (build-in data type of C#) and modelItemCollection (from the Autodesk Navisworks Manage 2013 API). Information like tag name, date created, and tag comment are stored as strings. All models associated with the tag are stored as a collection in the data type modelItemCollection. To support multiple tags, the generic data type List<type_name> of C# was used, since it offers common array operations such as add, remove, and can dynamically change its own length.

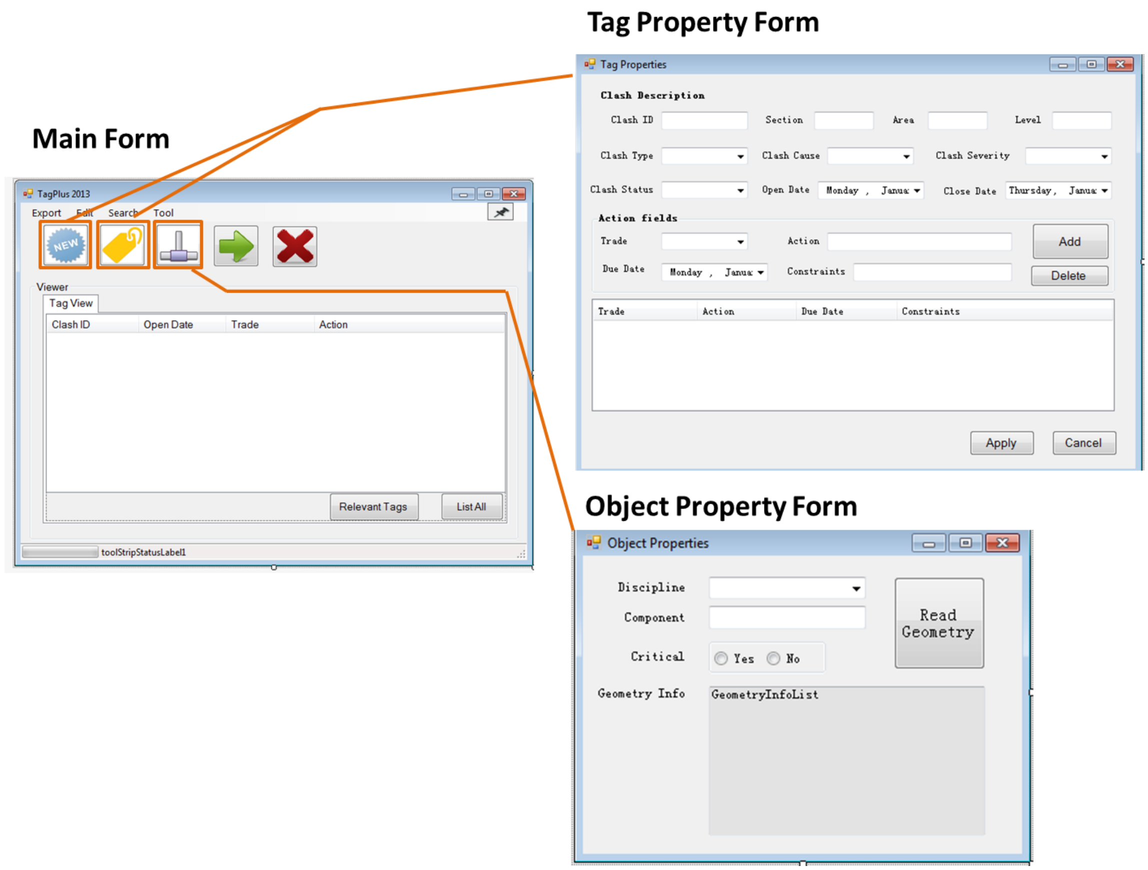


Figure 10: GUI of the plugin

The API of Autodesk Navisworks Manage 2013 plays an important role in connecting the models and the tags. ModelItemCollection is a build-in class of the .NET API of Autodesk Navisworks Manage 2013. This data structure allows the operations of reference to a collection of models, and thus it can be considered as a pointer to an array of models. By making ModelItemCollection a data member of the tag class, model elements can be directly connected to tags. More importantly, the TimelinerTask class was used to store the information of the tag. Since all changes made by the users are within the temporary memory space of the plugin, which will be released when the plugin is closed, it is important to find a storage format that can be saved into files on disk. Ultimately, TimelinerTask, which has data structures including a chain structure composed of strings and a modelItemCollection, was used to store the tags. TimelinerTask is typically used to store the information of construction sequences. In order to distinguish these two kinds of uses, a redundant string “TAG” was added to the top of the string chain of TimelinerTasks that are used to save tags. Thus, the plugin can automatically detect tags from all TimelinerTasks and generate a tag library.

3.4.3 Prototype demonstration

The prototype system was tested internally in the lab by the authors and externally by two industry practitioners. In the internal test, the prototype plugin was demonstrated on Windows 7 operating system on personal computers in a retrospective test case using coordination data from a construction project on an airport rental car facility in the United States. The $155.5 million project commenced in the spring of 2013 and is scheduled for completion in the fall of 2015. This project consists of a 1.6 million square feet (148,645 m2) five level cast-in-place concrete structure including: circulation cores, ready/return area (RR), customer service building (CSB), quick turn-around area (QTA), ground level service yard, pedestrian access bridge across existing parking garage, new and modified site circulation roads and parking lots, and ramps and elevated roadways. The prototype demonstration was done using the coordination data of the customer service building (CSB) from August 2013 to February 2014. The project’s BIM coordinator used the viewpoint function in Autodesk Navisworks Manage to document and manage the clashes. As shown in Figure 11, nine folders were created to group the viewpoints by their severity level (e.g., “01 Hot List” and “02-Outstanding Items”), status (e.g., “03-Resolved Items”) and responsible trade (e.g., the sub-folder “01. Multiple Disciplines” and “05. Architectural” within the folder “02-Outstanding Items”).

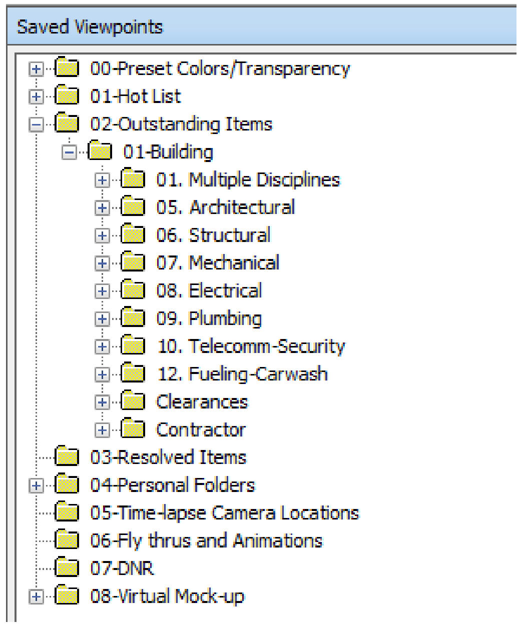


Figure 11: Saved viewpoints from the test case project

Clash relevant information was included as folder names or viewpoint descriptions as shown in Figure 12, which was not efficient to manage, search or keep track of changes. In the prototype system, tags are associated with model elements instead of static 2D images and the clash information is categorized as discrete attributes, which enables searching or grouping clashes by specific attributes for analysis. In the example shown in Figure 12, outstanding items in viewpoint documentation were labeled as clash severity "Medium" in the prototype system; the folder "Plumbing" was represented as the responsible trade in Action fields; the area information ("East Core") included in the viewpoint description was also represented in the model-based system; model-related information, such as the clashing beam and plumbing pipe were stored in the object property form associated with the two model components; additional comments can be stored as constraints in the action fields. In addition, the prototype system also captured information that was originally not documented in the viewpoints, including the clash ID, section, level, clash type, clash cause, clash status, open and close dates, as well as action items. The prototype system can capture multiple action items associated with a clash to track the sequence of changes made to the model.

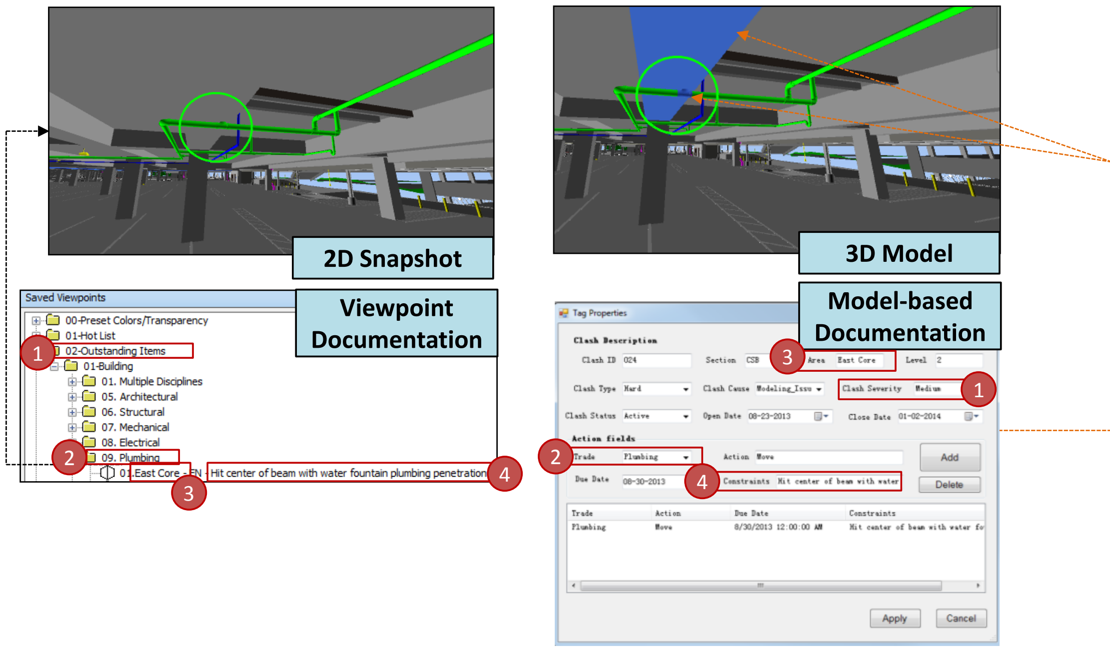


Figure 12: Comparison between viewpoint documentation and model-based documentation

224 clashes in the test case project were documented using the prototype system and exported to an external data spreadsheet. The functional requirements identified in section 3.4.1 were tested and the results are summarized in Table 13.

Table 13: Retrospective test on the functional requirements

Functional Requirements	Current Viewpoint System	Tag-Plus System	Implementation Challenges
Create tag	Yes	**Yes**	Ease of information input (automatic populated information for data items such as clash ID, level and area is desired)
Link tag to model	No	**Yes**	N/A
Delete tag	Yes	**Yes**	N/A
Edit tag	Yes	**Yes**	Extensibility and flexibility of the input attributes (allowing the users to change or modify input attributes)
Edit object information	No	**Yes**	To enable editing object information of multiple model elements at one time; Some geometric information cannot be automatically extracted because of the authoring software and the limitations of reasoning geometric information using current API (Autodesk Navisworks Manage 2013)
Save tag	Yes	**Yes**	To enable linking the tag to viewpoint in addition to model components
Search tag	No	**Yes**	N/A
Group tag	Yes (Manual)	**Yes (Automated)**	N/A
Export tag	Yes	**Yes**	To enable exporting data to various formats

As compared to the tag functions of current tools, the most important improvements of the proposed system is enabling a categorized documentation template as well as enabling the connections between tag and associated model element(s).

Consequently, the coordination information can be stored as parametric information of the model instead of static 2D snapshots that have no connections to the model. Changes that are made or need to be made can be easily associated with model elements, which can ease the efforts of organizing and managing the design coordination comments by manually referencing the model. Geometric information can be automatically extracted from the model and associated with the design coordination information. In addition, searching and grouping functions also facilitate efficient management and organization of the clash information in design coordination. Moreover, the time required for information input using the prototype system does not significantly increase compared to current practice and would be further reduced once the challenges identified in Table 7 are addressed (e.g., automated populating information such as clash ID, area and level, and editing object information for multiple components at one time).

In the external tests, two BIM coordinators working for two general contractors participated in the validation tests. The two subjects were selected because their daily work responsibilities were preparing clash reports and coordinating the models and are very familiar with the clash detection functions in Navisworks. The goals of the external tests are to assess the usability of the system and possibility to integrate such system into current work practice. Before the tests, each subject went through a 15-minute training session in which the basic function and concepts in the system were introduced and demonstrated. The subjects were then asked to install the plugin in their machines and test it with their project data. The testing duration was one week. Feedback was provided by the subjects at the end of the tests. In general, the subjects found the system helpful in standardizing the documentation content and enabling searching of the clash information. One subject said that he usually spend about 24 hours a week in coordination, either preparing clash reports or leading the coordination meetings. In his current project, one coordination meeting often takes 3 hours. This effort of streamlining the documentation process is important in reducing the time for documenting clash information and conducting analysis of the clash data on weekly or monthly basis. Several suggestions were provided to improve the "TagPlus" system and were presented below.

In the retrospective tests, several implementation challenges were identified for future improvements of the proposed system.

1) Information consistency across multiple versions of coordination models is the main challenge encountered. Throughout the design coordination process, the coordination model is typically updated on a weekly basis with amended or new information. In the prototype system, clash-relevant information is stored as timeliner tasks which is associated with model components, so the attached information will be lost if the component is removed in an updated model. Currently, this challenge is addressed by merging and managing updated information in an external database system. An alternative solution is adding a link between the tag and viewpoint (2D snapshot of the clash), so that the tag will not be lost when the model component is modified or removed.
2) Another potential improvement is enabling automatic populated clash ID, level, and zone to ease the inputting effort. Clash ID and location information are important to specify and locate a particular clash, but repetitively inputting this information for each clash is time-consuming and can be facilitated by automatic populating the information based on previous input or predefined values. It was also suggested to integrate the available data in clash detective tests in Navisworks into the plugin system.

3) Due to different data representation and capability in various authoring tools, object information is usually not available for direct extraction. For example, in many projects, trade and component information can only be found in the model layer description. Therefore, the user needs to input such information in the object property form to accurately describe a model object. This process can be accelerated if object information can be easily extracted or object information of multiple model elements can be edited at one time.
4) Some geometric information cannot be automatically extracted because such information is not explicitly provided by the authoring software and is difficult to calculate due to the complexity of reasoning geometric information using current API (Autodesk Navisworks Manage 2013)
5) The current input parameters can only be changed by modifying the codes, which can be customized. However, it is important to keep the parameters consistent in order to perform data analysis for knowledge exploration.
6) A future version of the prototype system should also allow exporting data to multiple formats (the current version only supports JSON, which is a lightweight data-interchange format that is human-readable and also easy for machines to parse and generate). Another suggestion is to enable populating clash reports from the plugin system so that it can be used in the coordination meetings.

Compared to other KC techniques, the proposed approach enables ‘live’ capture of process knowledge with IT support instead of relying on the knowledge developer to gather and interpret the data after knowledge has been generated and exchanged and the decisions are made. This approach also allows the construction management companies to build their organizational database for specific types of projects (e.g., healthcare, residential or commercial), types of contracts (e.g., design-build, design-bid-build, construction management at risk, or integrated project delivery), or group composition.

3.5 CONCLUSIONS

This research question aims at exploring the feasibility and potentials of capturing and representing process information in the model-based design coordination process. Since the design coordination is an iterative process, the information (such as clash description and proposed solutions) generated during this process involves significant amount of construction knowledge. Such information, if documented properly, can be utilized as a basis for construction knowledge formalization. In current practice, process information is seldom documented formally. Current commercial software only supports creating tags or notations on static viewpoints of the model, which are basically 2D screenshots. No connection is established between the tags and the model elements, which makes it difficult, if not impossible, to perform analysis using those tags and screenshots. The relationship between the proposed solution and associated model elements needs to be studied and extracted as computer-interpretable rules so as to support construction knowledge formalization and integration in early design.

Through the prototype development and demonstration, this research initiates a new approach of capturing model-based process information using BIM and an auxiliary tool with augmented tag functions. The prototype system was demonstrated using design coordination data of a customer service building (CSB) in a car rental facility project. 224 clashes in the test case project were documented using the prototype system. Additional functional requirements, such as linking tags to the model, search clashes by keywords or by model elements, editing or extracting object information, were successfully implemented in the prototype system. Implementation challenges are identified for future improvements of the proposed system.

This research indicates that process information can be captured and represented with connections to the model, which serves as a basis for developing model-based information capture tools with similar purposes. With the prototype system, BIM engineers can explicitly visualize what model components a tag refers to and all the tags that are attached to certain assemblies. They can also group and search for specific information as needed. Such "live" knowledge capture system enables the project team to systematically capture process information during the work process, which provides an alternative source for knowledge discovery. The categorized data items enhance the capability of future data analysis and provide the basis for knowledge exploration.

Chapter 4 Knowledge Discovery of Spatial Conflict Resolution in BIM-enabled MEP Design Coordination using Data Mining Techniques

This chapter will answer research question 3: What knowledge can be extracted and reused using the captured information. Knowledge discovery in a computer interpretable manner is a critical step toward effective construction automation. This research aims to explore knowledge discovery of spatial conflict resolution in building information modeling (BIM)-based mechanical, electrical, and plumbing (MEP) design coordination with the data captured from previous projects using data mining techniques.

4.1 INTRODUCTION

Design coordination in 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 (Tatum and Korman 2000; Korman et al. 2003). The general concept of MEP coordination involves defining locations and dimensions of MEP components in congested spaces to avoid interference between pairs of disciplines which includes Heating, Ventilation and Air Conditioning (HVAC; referred as mechanical in this research), electrical, plumbing, structural, architectural, and fire protection, while complying with design and operations criteria (Korman and Tatum 2001; Korman et al. 2003). Nowadays, Building Information Modeling (BIM) has been widely used in the building construction industry in the United States, mostly for design or trade coordination (Hartmann and Fischer 2007; Becerik-Gerber and Rice 2010). With the assistance of BIM, the construction team can perform automated clash detection to identify clashes between systems more efficiently and intuitively, as compared to paper-based design review (Songer et al. 1998; Staub-French and Fischer 2001; Staub-French and Khanzode 2007; Khanzode et al. 2008; Leite et al. 2011). However, the process of resolving MEP design conflicts is still very ad hoc and experience-driven. Most clashes discussed in coordination meetings have repetitive patterns; nonetheless, the majority of knowledge involved is tacit knowledge based on specialized expertise and experiences, which is difficult to centralize or formalize.

Although researchers have conducted case study research to discover and formalize design coordination knowledge (Korman et al. 2003; Tabesh and Staub-French 2005; Staub-French and Khanzode 2007; Leite et al. 2009; Khanzode 2010), the knowledge formalization process is very expensive in terms of the requirements on time, cost and human resources and the formalized knowledge available to support decision making during design coordination is insufficient. The lack of formalized knowledge for MEP design conflict resolution and inadequate historical data available hinders the attempts towards streamlining and expediting the decision making process, and also impedes knowledge reuse and transfer across different disciplines (e.g., between design and construction), different entities (e.g., between experienced workforce and novices) and different projects. Because of the emergence of BIM and the current limited expertise in the United States construction industry, general contractors have started to hire novice engineers who are proficient in operating the coordination software systems but have limited practical experience in MEP design and coordination. A challenge that needs to be addressed is how to formalize and transfer experiential knowledge to next generation professionals. Experiential knowledge often includes tacit knowledge which is difficult to be articulated or generalized into rules or guidelines (Nonaka and Takeuchi 1996).

The first two research questions (1 and 2) have answered what information needs to be captured and how to capture such information. This chapter focuses on analyzing the data captured from previous projects using data mining techniques. It is envisioned that by capturing and analyzing historical data relevant to coordination issues, tacit knowledge of MEP design conflict resolution can be semi-automatically extracted and formalized, which will reduce the reliance on individual researchers and provide efficiency in hidden pattern recognition. This chapter presents a new approach to formalize knowledge and discusses the feasibility, potential benefits as well as the challenges of implementing the proposed knowledge discovery method in the MEP coordination process. The objectives of this research question are: 1) to discovery meaningful patterns from the captured historical data, 2) to build a predictive model to assist future decision making and narrow down the search space for the decision makers, and 3) to train novice engineers to conduct design coordination tasks with decision support based on past project data.

4.2 LITERATURE REVIEW

This section provides an overview of the research areas relevant to this study, which include data mining in engineering domains and expert-novice research and problem-based learning.

4.2.1 Data mining in engineering domains

In any engineering field, a great amount of data is produced during an artifact's life cycle (Garcia et al. 2009). Data management technology had provided the means for organizing and storing information; however, having information available is a necessary, but not sufficient, condition for learning (Garcia et al. 2009). It is important to retrieve and digest information to craft new knowledge from the stored information. Researchers have conducted procedural or statistical analysis to learn from the past, especially for critical decision-making processes (Maher and de Silva Garza 1997; Soibelman and Kim 2002). Because of the large amount of data and the complexity of the targeted problems, making sense of engineering project data often overwhelms human capabilities, even for a specific domain area or company. In response to this challenge, data mining (DM) has become an attractive alternative to classic mathematical models when applied to specific tasks such as problem diagnosis and failure prediction (Varde et al. 2008). DM is the process of discovering relevant knowledge from large data repositories (Fayyad et al. 1996). Many DM techniques and algorithms have been applied to assist decision-making in the engineering domains, ranging from clustering or association rules (unsupervised) to classifications or prediction (supervised). Examples of these applications include knowledge transfer from maintenance to design for aero-engine artifacts (Jadhav et al. 2007), identifying calibration models in building structural components (Saitta et al. 2005), and eliciting the customer's project requirements (Lo et al. 2007).

In the AEC industry, a large amount of data is generated and circulated in every project and also during MEP design coordination. It is estimated that a typical building project generates 150,000 separate documents, including technical drawings, legal contracts, purchase orders, requests for information and schedules ("New wiring" 2000). Many of these documents are textual. Based on this fact, data mining can be a promising way for knowledge discovery and continuous improvement. In the 1980's, software developed for design purposes led to early attempts to use heuristics derived from explicit human experience in a limited compilation of constructability knowledge (Kirby et al. 1991). Later on, Skibniewski et al. (1997) investigated the use of machine learning approaches for constructability analysis. Soibelman and Kim (2002) suggested that the knowledge discovery application might be used to identify time overruns in construction activities by using decision trees and neural networks using resident management data. It has been validated in previous studies that knowledge formalization using historical data has potential strength in the experience-oriented construction industry. Data mining techniques were also implemented in construction document classification (Caldas and Soibelman 2003), building maintenance data analysis (Reffat et al. 2004), asphalt paving data analysis in transportation projects (Nassar 2007), defect detection in sewer pipeline inspection (Guo et al. 2009), and water distribution breakage data analysis (Oliveira et al. 2011).

The current state of practice for knowledge documentation in MEP design coordination is unstructured and informal. The 3D model does not provide proper documentation templates to capture important attributes and decisions in MEP coordination meetings so that the information can be referenced and analyzed for knowledge formalization and knowledge reuse (Staub-French and Khanzode 2007). Currently, large amounts of data related to MEP design coordination are not available and there is no guideline for a structured documentation process, which is a big challenge for using a data-driven approach to formalize MEP design conflict resolution knowledge.

4.2.2 Expert-novice research

Expertise in the AEC industry is often related to experience, domain knowledge, intuition and contextual awareness, which is mostly tacit. In order to retain appropriate expert knowledge to train and assist novices, it is important to understand the knowledge gap between experts and novices in the target problem. Expert-novice studies are often conducted to understand the performance differences across levels of expertise in different problem domains. In previous studies, such performance differences were explained with different possible factors, including but not limited to, memory ability (Gobert 1999), knowledge content (Johnson et al. 1981), knowledge organization (Chase and Simon 1973; Chi et al. 1981), understanding of the problem (Perkins and Grotzer

2000), information search strategies and information delivery methods (Kiziltas et al. 2010). Specifically, design process and cost estimating studies are most relevant to this research. Ahmed et al. (2003; 2004) studied the differences of how novice and expert designers approach design tasks in the aerospace industry to identify the knowledge needs for novice designers in the engineering design process. Results showed that novice designers tended to use a particular pattern of trial and error, while experienced designers used design strategies that the novice designers were not aware of. Other studies also indicated that novice designers tended to reason backwards using a deductive approach, while experienced designers tended to reason forward, and when solving more complex problems, to alternate between forward and backward reasoning (Waldron and Waldron 1996; Zeitz 1997). Kiziltas et al. (2010) compared the behaviors between experienced and novice cost estimators in information pull and push methods, which showed that novices can behave like experienced estimators when information relevant to a decision is pushed to them. In the construction domain, few studies have investigated the differences between experienced and novice design coordinators when performing coordination tasks.

In previous expert and novice studies, two types of knowledge elicitation approaches were used: observational studies and empirical/experimental studies. Observational studies, also referred as ethnographical approach, collect data from observations within the natural setting to minimize external influences from the investigator on the observed subjects (Hung 2003; Ahmed and Wallace 2004). Experimental studies collect data from designed activities in a laboratory environment (Arnold et al. 2006; Atman et al. 2007; Kiziltas et al. 2010). The data collected can be used to discover disparity and similarity or to prove/disprove pre-defined hypotheses.

4.2.3 Problem-based learning

Problem-based learning (PBL) is a student-centered instructional methodology in which students are presented real-world problems and learn through the experience of problem solving (Hung et al. 2008). It was originally designed to prepare medical students for solving problems in clinical settings (Barrows and Tamblyn 1980; Hung et al. 2008; Schmidt et al. 2011) and was later adopted in various fields such as architecture (Maitland 2005), business administration (Merchant 1995) and chemical engineering (Woods 1996). PBL aims to facilitate active and self-directed learning and help students develop problem-solving skills, as well as consolidated domain knowledge (Hmelo-Silver 2004). PBL is sometimes referred to as project-based learning (Fruchter and Emery 1999), team-based learning (Livingstone and Lynch 2000), work-place learning (Zolin et al. 2003) or "problem-, project-, product-, process-, people-based" learning (Fruchter 1999). PBL provides students with an opportunity for experiential learning in a supported environment that will facilitate the transfer of knowledge from the educational context to the professional context (Candy and Crebert 1991). In the AEC industry, PBL is also applied to assist learning in various educational programs (Fruchter 1999; Cannon and Leifer 2001). Design coordination is one of the engineering subjects that require substantial problem-solving skills. PBL can play an important role to enhance students' ability of critical thinking, problem-solving and decision-making. While the theoretical ground of design coordination is straight-forward and easy to understand, the implementation usually requires considerable experiential and tacit knowledge. How to provide an environment for PBL in design coordination is a problem worth addressing, but not yet adequately studied.

4.3 Research Approach

This research is composed of four major steps: data preparation, data exploration, data mining and novice experiment. Data preparation focuses on cleaning and formatting the raw project data to formats that are consistent over projects and can be used to perform data mining tasks. This step is the most important yet most time-consuming one. The quality of data has significant impacts on the model performance and the reliability of results. The next step is data exploration, which summarizes and roughly describes the data distribution and trends in general. Through data exploration, potential patterns and targeted data mining tasks were identified. The main objective is to assign a solution (including responsible trade and action item) to a new clash based on its features and the record of clashes for which solutions are known. In data mining, classification aims to construct predictive models based on training data sets to predict dependent categorical variables. Therefore, classification is applied in this study. The dependent variables in this study are responsible trades and action items to resolve the clash. Multiple classification algorithms were applied to reach the optimal classification performance. The optimal predictive models were then selected and tested in a novice experiment, in which the effectiveness of the data-driven decision support system was examined. Detailed explanation of each step is presented in the following sections.

4.3.1 Data preparation

Design coordination data was collected from three new construction projects to build the database for analysis. Table 14 provides a summary of these projects. Project A is a 120,000 square feet five-story medical office building, which broke ground in July 2012 and finished construction in early 2013. Project B is a new 7,706 seat football stadium and 107,613 square feet Student Union Center, which started construction in March 2012 and reached substantial completion June 2013. Project C is a new rental car facility at an airport, which consists of 800 public parking spaces, 2,992 rental car stalls, a new customer service building, a new Quick Turn Around (QTA) facility and roadway construction. This project broke ground in Spring 2013 and is estimated to be complete in Fall 2015. The design coordination data of the customer service building was collected and included for analysis in this study. Three different general contractors were hired for the three projects. Design coordination of MEP systems in the three projects was all conducted using Autodesk Navisworks Manage. Viewpoints were used as the main documentation of clashes with supporting documents such as clash reports or clash logs.

Table 14: Project summary

Project	A	B	C
Project Type	Medical Office building	Stadium and Student Union	Rental Car Service Building
General Contractor	GC1	GC2	GC3
Contract Type	IPD	CM at Risk	Design-Build
Coordination Period	5/5/2012-12/6/2012	7/27/2012-2/20/2013	8/23/2013-2/5/2014
Total Clashes	329	346	375
Coordination Software	Autodesk Navisworks Manage	Autodesk Navisworks Manage	Autodesk Navisworks Manage
Clash Documentation	Viewpoint+Clash Report (pdf)	Viewpoint+Clash Log (xls)	Viewpoint

Coordination models and clash-related documents were gathered from the three projects, from which coordination data was extracted and transformed into a consolidated database. For projects A and B, data transformation was conducted manually by examining the coordination models, referencing the information available in saved viewpoints and clash documents (clash reports or clash logs) and comparing model changes between different versions of coordination models. For project C, a model-based data capture system prototyped as an add-on to Autodesk Navisworks was used for clash documentation. Based on the design coordination representation schema developed previously by the authors (Wang 2014), clash features documented in the database include: model version, clash ID, floor level, area/zone, clashing trades, clashing objects, directions (orientations) of the clashing objects, number of trades, number of clashing objects, cause of the clashing, clash type, open date, close date, resolution duration, responsible trade and action. Additional information was documented as notes for each clash. Table 15 shows a complete list of the clash attributes.

Table 15: Attribute descriptions

Category	Attribute	Type	Example
Clash Description	System	Nominal	Mechanical
	Object	Nominal	Light fixture, Grille
Clash Context	Direction	Nominal	Horizontal vs Vertical (H-V)
	Number of trades	Numeric	2, 3
	Number of objects	Numeric	2, 3, 4, 5
Clash Evaluation	Clash severity	Nominal	High, medium, low, none
	Clash type	Nominal	Hard, barely clipping, clearance, soft
	Clash cause	Nominal	Modeling error, coordination issue, design issue
	Responsible trade	Nominal	Plumbing (P)
	Action	Nominal	Move, raise, lower, reshape
Clash Management	Clash ID	Nominal	0102, 34
	Level	Numeric	0, 1, 2, 3 (0: underground)
	Area	Nominal	1406 Corridor, A, CSB plaza
	Open date	Date	8/21/2012
	Close date	Date	9/4/2012
	Due date	Date	9/11/2012

The model naming conventions, terms used and information available in the three projects were different. In order to merge data into an integrated database, data was transformed following consistent feature definitions. Missing and unclear data was removed. After data preprocessing, 1,050 data items were used for further analysis.

4.3.2 Data exploration

Data exploration aims to present an overview of the data and to help identify appropriate data mining tasks and directions. The distribution of clashing trades (pair-wise), clashing cause, clashing type, responsible trades, actions, and count of clashes in timeline are presented in the Results section.

4.3.3 Data mining

The data mining task used in this research was classification. Classification is a supervised data mining technique that assigns items in a collection to target categories or classes (Fayyad et al. 1996). The goal of classification is to accurately predict a certain outcome based on a given input. The data used to train the classifier and build the classification model is called the training set. A classifier is used to find relationships between the values of independent variables (explanatory variables) and the values of dependent variable (the class to predict). Various classification algorithms can be used find the relationships, which are summarized in a model and tested in a different data set (test set). The prediction accuracy is used to evaluate the goodness of fit of the model. The selection of algorithms depend on the size of training set, data features, dimensionality, prediction speed and memory requirements. Some commonly used and well-performing classification algorithms include Naïve Bayes, logistic regression, decision trees, and support vector machine (SVM). Five types of classifiers (i.e., Naive

Bayesian, regression model, tree-based classifiers, rule-based classifiers, and instance-based classifiers) were examined in this research.

The Naive Bayes (NB) classifier uses the Bayes theorem to predict class labels assuming that the input attributes are conditionally independent of each other. It is simple to implement and usually performs well in practice. If the NB conditional independence assumption actually holds, a Naive Bayes classifier will converge quicker than discriminative models like logistic regression, so less training data is needed. Some algorithms include BayesNet, NaiveBayes, NaiveBayesSimple and NaiveBayesUpdateable.

The regression models classifier is also commonly used for classification. Compared to NB, regression model does not require the features being correlated and can be easily updated with new data (using an online gradient descent method).. Algorithms include GaussianProcesses, IsotonicRegression, LinearRegression, LibSVM, MultilayerPerceptron, RBFNetwork, RBFClassifier, SimpleLinearRegression, SimpleLogistic and SMO. SVM has high accuracy in text classification problems with high-dimensionality, but it is memory-intensive.

The tree-based classifier is a tree-structured classification technique that is simple and widely used. It is easy to interpret and explain and works well even with outliers or when the data is not linearly separable. Some algorithms include ADTree, BFTree, J48, LMT, RandomForest, RandomTree, REPTree and SimpleCart. The disadvantage of decision trees is that they easily overfit. Ensemble methods like random forests (or boosted trees) have now become popular, because they are fast to train and scalable and usually produce lower classification errors and better F-score than decision trees.

The rule-based classifier classifies records by using a collection of 'if…then…' rules. Some algorithms include ConjunctiveRule, JRip, NNge. OneR, PART and ZeroR. The instance-based classifier uses some distance/similarity function to predict the class of an unknown instance based on the class of those training instances similar to it. Some algorithms include IB1, IBk, KStar and LWL.

In this study, the classification algorithms in these five categories were applied to the datasets using Weka 3.6.8 software which contains open-source machine learning algorithms for data mining tasks.

4.3.4 Novice experiment

An earlier study conducted by the authors (Wang and Leite 2014) compares the behaviors of experienced BIM coordinators with novices on model-based design coordination when performing certain coordination tasks. The results revealed that experienced BIM coordinators could locate relevant information and identify external information sources more efficiently, as compared to the novice coordinators. Experienced coordinators were also able to perform more in-depth analysis within the model based on their experiences. This experiment aims to investigate whether novices' performance will improve through Problem-Based Learning (PBL) when experiential knowledge extracted from past projects is made available to them. The purpose of the novice experiment is to validate the effectiveness of the data-driven decision support system in supporting novice engineers to perform design coordination tasks with the results generated by the selected classification models.

4.3.4.1 Subjects and procedures

An experimental study was conducted in a laboratory setting with 18 Engineering students who have fundamental understanding of MEP design coordination but limited project experience. The subjects were randomly assigned to Group A (9 students) and Group B (9 students). The study was conducted on an individual basis. Each student worked on a desktop computer and was provided 15 typical clash scenarios identified in a BIM in Autodesk Navisworks Manage. The 15 clash scenarios were typical clashes (i.e. most frequently occurred) selected from a federated model of a medical office building in the United States and were randomly divided into two groups: scenario 1-8 and scenario 9-15. For example, the most common clashes in this project were interferences between mechanical ducts and electrical conduits (as shown in Figure 13). The subjects were asked to act as BIM coordinators and prepare a clash report independently for discussion in an upcoming coordination meeting. The clash report should contain a description of each clash and possible solution or action items to resolve the conflict. A template form was provided to them for documentation.

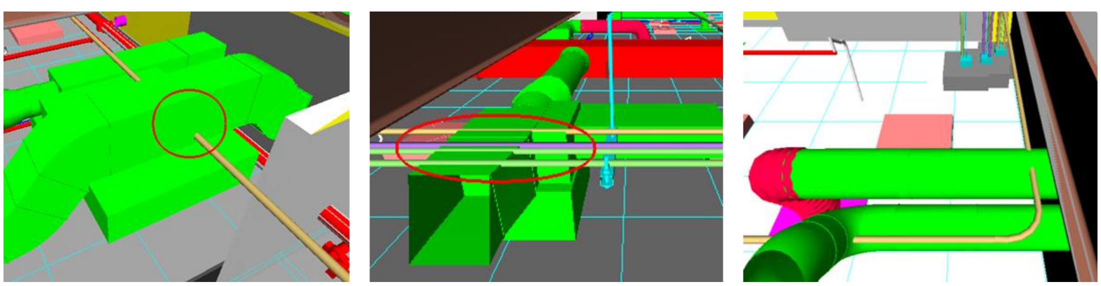


Figure 13: Examples of clash scenarios between mechanical ducts and electrical conduits

All subjects were asked to perform the designated tasks under two conditions: 1) without any external assistance and 2) with supportive information and suggestions based on past projects. A classification model was developed using coordination data gathered from multiple projects and was used to provide suggestions for the cases in the scenarios. As shown in Table 16, group A first performed the tasks without any assistance for scenarios 1 to 8 (this set of data was referred as A1) and performed the same tasks for scenarios 9 to 15 with decision support (A2). Group B first performed coordination tasks for scenarios 9 to 15 without assistance (B1) and then scenarios 1 to 8 with decision support (B2). Information provided as decision support included a brief description of clashing trades (e.g., MDUCT vs ELEC, which stands for mechanical duct and electrical system), clash type (e.g., Hard clash), clash cause (e.g., modeling issue), constraints (e.g., J-box location) and suggested solutions (e.g. reroute conduit).

Table 16: Summary of treatments

Group	Scenario 1-8	Scenario 9-15
A	Without decision support (A1)	With decision support (A2)
B	With decision support (B2)	Without decision support (B1)

The subjects' performances were captured by a screen recording application and the clash reports were stored using the same template. At the end of the experiment, each participant was asked to rate how helpful the decision support was in assisting their decision making in a scale from 0 to 5, where 0 is not helpful at all and 5 is very helpful. The participants were also asked to provide suggestions to enhance decision support for novice coordinators.

4.3.4.2 Data analysis

The videos captured were transcribed using a predefined coding scheme based on the subject's mouse movements to represent the sequence of steps taken to finish a task. Three types of analysis were conducted to study the impacts of intervention on the subjects' performance. The intervention in this experiment is the decision support provided to the subjects. As summarized in Table 17, three types of analysis were conducted:

- Different groups with the same treatment (A1 vs B1 and A2 vs B2);
- Same group with different treatment (A1 vs A2 and B1 vs B2); and
- Different groups with different treatment on the same scenarios (A1 vs B2 and A2 vs B1).

The treatment in this experiment is the provision of decision support. The performance metrics used in the analysis include the average time spent per clash and percentage of correct solutions.

Table 17: Summary of hypothesis tests

No.	Hypothesis	Test	Data
1	H_0: there is no significant difference between students' performance on scenario 1-8 and 9-15 under the same treatment. H_1: there is a difference	Independent-samples t-test	(1) A1 vs B1 (2) A2 vs B2
2	H_0: there is no significant difference between students' performance with and without decision support H_1: there is a difference	Paired-samples t-test	(3) A1 vs A2 (4) B1 vs B2
		Independent-samples t-test	(5) A1 vs B2 (6) A2 vs B1

The t-test is used to test differences in means between two groups. The t-test can be used even if sample sizes are very small, as long as the variables within each group are normally distributed. The independent-samples t-test evaluates the difference between the means of two independent groups (usually chosen by random selection). If the same group is tested twice (repeated measures), then the paired-samples t-test should be used. Since the sampling of group A and B were randomized, it was assumed that the average skill level and knowledge possession of groups A and B were not significantly different.

Therefore, two assumptions were made in this study: 1) the variables within individual group are normally distributed; and 2) group A and B represent the same population and they were not significantly different.

4.4 RESULTS

This section presents the summarized results from data exploration, data mining and novice experiment.

4.4.1 Data exploration

1,050 data items were documented in the clash database using selected features based on the design coordination representation schema. In the three projects, the trade that had the most clashes was mechanical (HVAC), followed by the electrical and plumbing trades (shown in Figure 14).

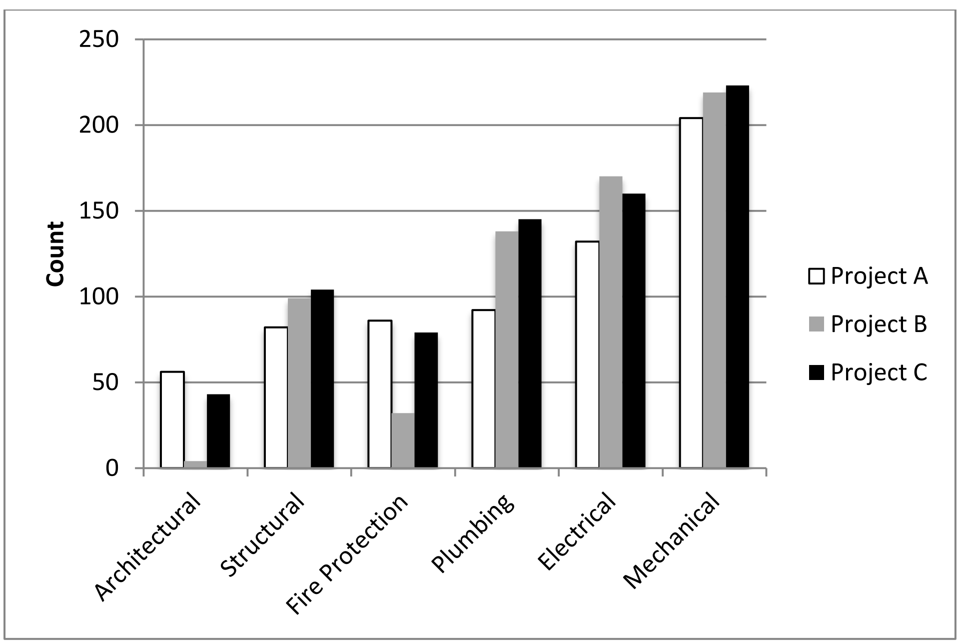


Figure 14: Counts of clashes relevant to specific trades

Figure 15 shows the counts of clashes between trades. In both projects, most clashes were found between mechanical and electrical systems. Project A also has comparatively more clashes between mechanical and structural, mechanical and fire protection, as well as mechanical and plumbing, while project B had more clashes between mechanical and plumbing, electrical and plumbing, and electrical and structural. The composition of clashes in projects may vary between different types of projects.

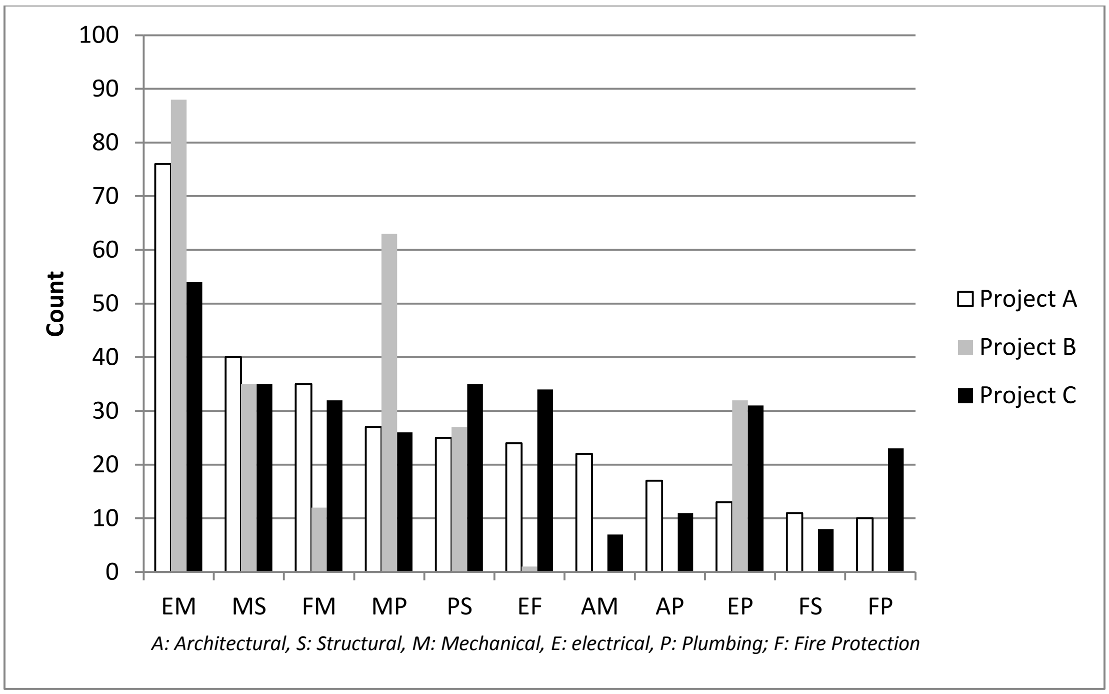


Figure 15: Counts of clashes by pairs of trades

Summarizing the results from three projects, the majority of clashes were coordination issues (65%) and modeling errors (32%), as shown in Figure 16. Coordination issues require more than one trade to reach an agreement on adjusting system locations and layouts to resolve a clash. For example, in a congested plenum, coordination issues were likely to occur between systems. Modeling errors were due to mistakes made by detailers or modelers from a subcontractor such as problematic system layouts which conflict with architectural or structural systems, or incorrect elevations. Only a small portion of the clashes were caused by design issues, in some cases Requests for Information (RFI) were issued for approval on design changes.

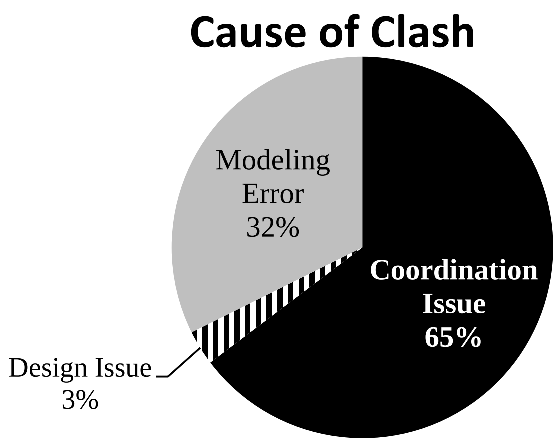


Figure 16: A summary of causes of clashes

As shown in Figure 17, 51% of the clashes were hard clashes, 32% were barely clipping, 9% were clearance clashes and 8% were soft clashes.

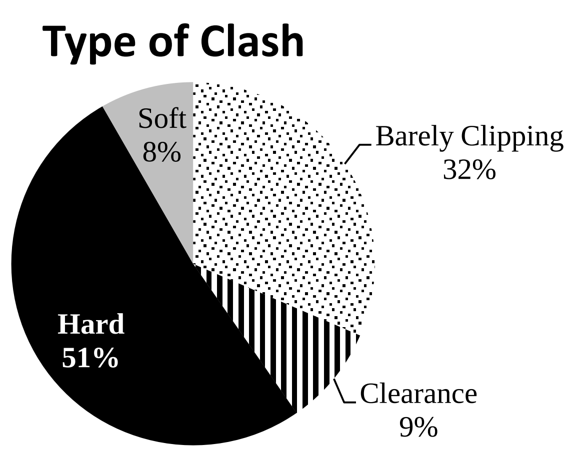


Figure 17: A summary of types of clashes

Figure 18 shows a summary of the responsible trades (the trade that took actions to resolve the clash). It is surprising to see that 39% of the clashes were resolved by the mechanical subcontractor, since it is commonly known that the mechanical system often has higher priority over other systems, which means that when conflicts occur, other systems usually need to take responsibility and move around the mechanical system.

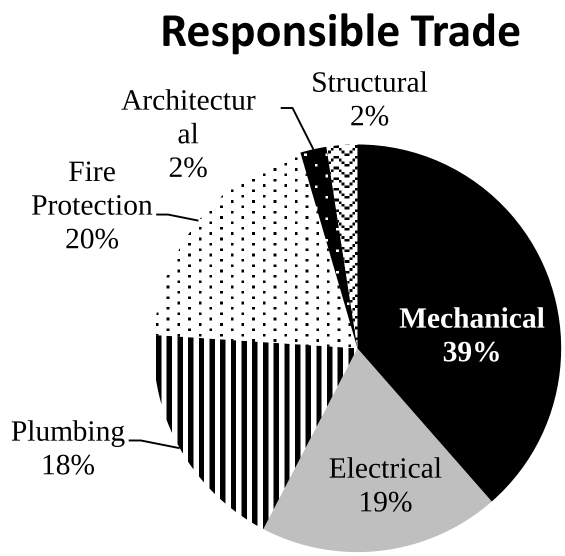


Figure 18: A summary of types of clashes

The most frequently applied solutions were moving clashing objects in horizontal directions (30%), raising (15%) or lowering (12%) objects and rerouting (13%) systems. 7% of the clashes were left to be solved by field adjustment.

Using the data, clashes can also be analyzed by floor level, by area or throughout the coordination period. Figure 19 shows the count of clashes in timeline for project A. It was observed that the number of new clashes as well as the resolved clashes both increased slowly at the beginning of the coordination stage; both the incremental rates of the counts of new clashes and resolved clashes increased dramatically between days 70 and 90; and at the end of the coordination period, the number of new clashes and resolved clashes reached another dramatic increase. This observation could be driven by deadlines, or due to specific coordination areas, such as mechanical rooms or corridors, where convoluted and dense MEP systems would easily clash with one another.

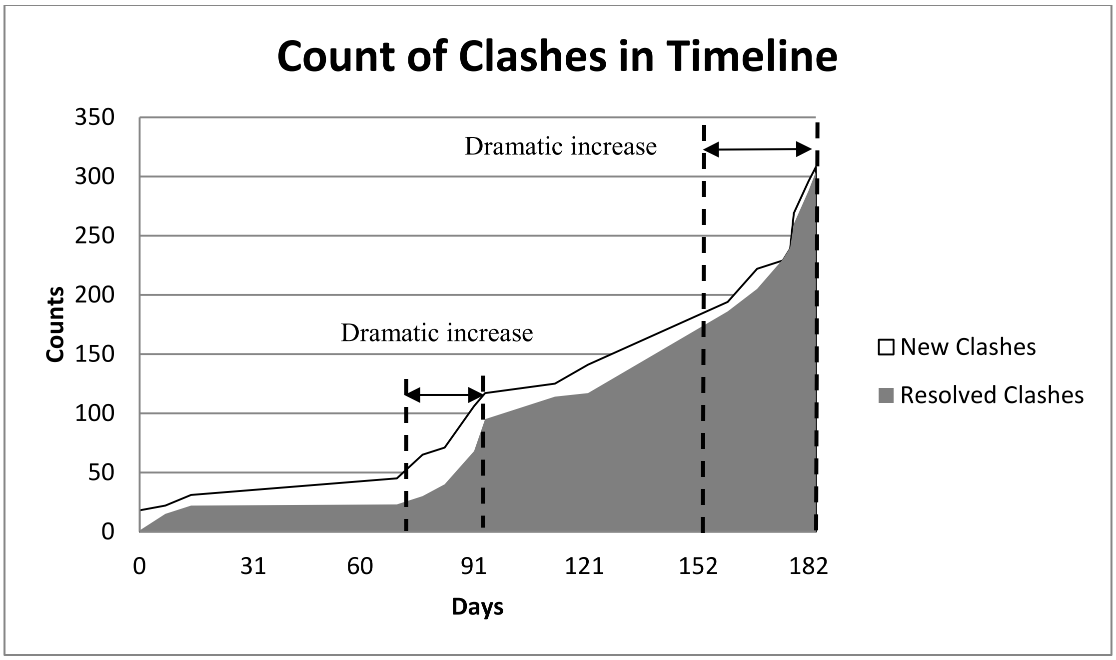


Figure 19: Count of clashes in timeline for Project A

It is easy to understand that larger systems such as mechanical usually has priority in the coordination process, however, results show that among all the clashes between mechanical and electrical systems, 51% of the clashes were resolved by the mechanical trade, 39% were resolved by electrical trade, and 10% of clashes were resolved by field adjustment. One possible explanation is that HVAC systems can change configuration (e.g., size of duct) according to specific needs, while other systems do not usually change in size. It is not obvious what rules were followed for clash resolution by simply looking at the data. Therefore, further analysis with data mining techniques was conducted to study the potentially hidden patterns.

4.4.2 Data mining

The dependent variables in this study are responsible trade and action. Classification in data mining involves employing a learning algorithm to identify a model that best fits the relationship between the attribute set and the class label of the input data. The model generated should accurately predict the class labels of input records. Given the difficulty of having experts explicitly and clearly articulate the rules behind the decisions made, the goal of classification is to predict solution classes based on previous decisions made using different learning algorithms. Classification models of the responsible trades were developed separately for pairs of trades. Two evaluation options were used to train and test classifiers: 1) 10-fold cross validation, and 2) assigned training and test sets.

Table 18 shows the results of 10-fold validation and assigned sets validation (training set: project A; test data = project B). The algorithms that have the best performance for each data set are listed below.

Precision was used as a performance metric for result comparison. The evaluation of a classification model's performance is based on the number of the test records it correctly and incorrectly predicts. The datasets with higher amounts of data tend to have better results with higher credibility. For example, in the classification between mechanical duct and electrical system, the models that have good performance are the ones generated by Naive Bayes (81.97%), JRip (77.05%), and KStar (75.41%). Important attributes include object, level, clash type, resolution duration, and number of clashing objects. Although there is an underlining order of preference, the actual situation is quite complicated. The classification models can help deal with the complexity and uncertainty of design coordination. Since the classification of actions is more complex, the precision rates are comparatively lower than the responsible trade classification. The results are shown in Table 19.

Table 18: Classification results for responsible trade

Data Set	**Attributes**	**Classification Algorithms**	**Precision**	
			10-fold	*Assigned*
MECH vs ELEC	Object, level, clash type, resolution duration, no. of clashing objects	*Bayes:* Na ïve Bayes	81.97%	65.41%
		Rule-based: JRip	77.05%	53.21%
		Instance-based: KStar	75.41%	50.32%
MECH vs FP	Object, level, clash type, resolution duration, no. of clashing objects	*Decision Tree*: NBTree	83.37%	42.40%
		Bayes: Na ïve Bayes	80.15%	23.48%
		Rule-based: DTNB	62.01%	20.14%
MECH vs PLMB	Object, level, clash type, resolution duration, no. of clashing objects	*Decision Tree:* ADTree	73.82%	56.63%
		KNN: LWL	71.70%	42.16%
		Bayes: Na ïve Bayes	65.83%	33.63%
ELEC vs FP	Object, level, clash type, resolution duration, no. of clashing objects	*Bayes:* BayesNet	78.13%	32.42%
		Rule-based: NNge	73.22%	53.22%
		Decision Tree: NBTree	71.79%	50.31%
ELEC vs PLMB	Object, level, clash type, resolution duration, no. of clashing objects	*Bayes:* Na ïve Bayes	65.03%	24.48%
		Rule-based: JRip	62.13%	23.12%
		Decision Tree: J48	60.00%	25.30%
PLMB vs FP	Object, level, clash type, resolution duration, no. of clashing objects	*Rule-based*: ZeroR	74.28%	24.33%
		Decision Tree: NBTree	72.67%	21.07%
		Bayes: Na ïve Bayes	72.67%	21.07%

*MECH=mechanical; PLMB=plumbing, ELEC=electrical, FP=fire protection, STR=structure, ARC=architecture

Table 19: Classification results for action

Classifiers	**Classification Algorithms**	**Precision**	
		10-fold	*Assigned*
Bayes	Na ïve Bayes	67.21%	43.12%
Regression	Logistic	65.57%	40.05%
	MultilayerPerceptron	56.39%	53.33%
	SMO	67.21%	46.31%
Instance-based	LWL	53.93%	32.37%
Rule-based	DTNB	70.49%	50.64%
Tree-based	RandomForest	67.21%	42.18%
	FT	70.49%	44.96%

The precision rate using 10-folder cross validation is higher than the assigned set validation. One explanation is that the size of the training set is smaller using the assigned set validation. Furthermore, resolution criteria used in different projects may vary due to the project setting, coordination schedule, trade priority in a specific area and other influencing factors, which were not included in the analysis. The precision rate of responsible trade classification can reach 83.37% (ranging from 60.00% to 83.37%) and 73.77% (ranging from 53.39% to 73.77%) for the action item classification. The Bayes classifiers and decision tree classifiers outperformed other classifiers (regression, instance-based and rule-based) in the coordination resolution problem.

4.4.3 Novice experiment

This section summarizes results from the statistical analysis. Hypothesis 1 aims at learning the effects of different sets of scenarios on subjects' performance. This is mainly to ensure that this factor of scenario sets does not have significant impact on subjects' performance, since there is no evidence that these two sets of scenarios (scenario 1-8 and scenario 9-15) have the same levels of complexity and difficulty for design coordination. Hypothesis 2 aims at learning the effects of decision support on subjects' performance.

The test results are summarized in Table 20. As summarized in Table 17, two hypothesizes were tested and three types of analysis were conducted: i) different groups with the same treatment (A1 vs B1 and A2 vs B2), ii) same group with different treatment (A1 vs A2 and B1 vs B2), and iii) different group with different treatment on the same scenarios (A1 vs B2 and A2 vs B1). The treatment in this experiment is the provision of decision support. The performance metrics used in the analysis is the average time spent on each clash scenario and percentage of correct solutions.

Table 20: Summary of test results

Test	Result	
Hypothesis 1: (1) A1 vs B1	Time: Accuracy:	t= - 0.695, df =16, sig = 0.497 (>0.05) →Accept t= 1.532., df =16, sig = 0.744 (>0.05) →Accept
Hypothesis 1: (2) A2 vs B2	Time: Accuracy:	t= - 0.968, df =16, sig = 0.347 (>0.05) →Accept t= 1.114, df =16, sig = 0.673 (>0.05) →Accept
Hypothesis 2: (3) A1 vs A2	Time: Accuracy:	sig = 0.001 (<0.05) →Reject sig = 0.003 (<0.05) →Reject
Hypothesis 2: (4) B1 vs B2	Time: Accuracy:	sig = 0.001 (<0.05) → Reject sig = 0.004 (<0.05) → Reject
Hypothesis 2: (5) A1 vs B2	Time: Accuracy:	t= 1.755, df =16, sig = 0.038 (<0.05) → Reject t= - 0.758, df =16, sig = 0.097 (>0.05) → Accept
Hypothesis 2: (6) A2 vs B1	Time: Accuracy:	t= - 3.580, df =16, sig = 0.003 (<0.05) → Reject t= - 0.235, df =16, sig = 0.136 (>0.05) → Accept

The value "sig" shown in Table 20 is the p value of the t-test. The interpretations of the above results are: 1) there is no significant difference between students' performance on scenario 1-8 and 9-15 under the same treatment; 2) there is significant performance difference within the same group of students with and without decision support; 3) there is significant difference between the average time spent with and without decision support, but there is no significant difference between the accuracy rate with and without decision support. In summary, the data-driven decision support can significantly reduce the time needed to complete coordination tasks by novice engineers; however the accuracy of the predicted results still needs to be improved.

The statistical findings are also consistent with the feedback that was obtained through the open ended questions. The average rating of the helpfulness of decision support provided is 4.1 (on a scale from 0 to 5, where 0 is not helpful at all and 5 is very helpful), which means the majority of the subjects thought the assistance provided was helpful. A detailed examination on the feedback revealed the reasons that can be used to explain the results from the statistical analysis. Based on the feedback from the participants and the observation from captured videos, the information provided by the decision support system helped them understand the clashes more efficiently and effectively. The decision support also helped the participants form a more organized structure to document clashes and solutions and facilitated wider consideration by including multiple factors (such as design intent and constraints) during the decision making process. More than 50% of the participants noted that the decision support system was helpful in terms of providing information for double checking the solutions. Furthermore, the participants also noticed that the solutions generated based on past project data were not always correct and accurate. This provides some explanation of why the percentage of correct solutions did not significantly increase when decision support was provided, which also implies that the accuracy of the current decision support system still needs improvement. Another possible explanation is that the scenarios included in this study were common clashes that are straightforward to resolve, even for novices. Results may vary if more complex clashes are considered.

4.5 Conclusions

Formalizing coordination knowledge from collective historical data can be a promising approach because it can make use of past project experience, reduce the subjective impact of individual bias and provide considerable accuracy of prediction. The information and knowledge derived from project databases can continually inform intelligent decision making and assist in next generation design processes. With this perspective, this research indicates that if past MEP coordination data is documented properly, it can be used to make accurate predictions for future issues and conflicts. Using data mining techniques to explore and reuse tacit knowledge is feasible but also requires massive data to achieve satisfying model performance. The current challenge of data collection and preparation is that there is a lack of standardization for collecting and storing project data in the construction industry. This becomes a critical barrier to implement data mining techniques for knowledge management in the construction industry. For MEP design coordination, a complementary model-based documentation template needs to be developed to support automated or semi-automated data acquisition. Moreover, the most efficient way to get more labeled data is to have practitioners label data as their natural tasks. This research also demonstrates the effectiveness of training and assisting novice engineers with data-driven decision support in a problem-based learning environment. Results show there is significant reduction in time for novices to perform coordination tasks with decision support. Future research will focus on improving the prediction accuracy of the classification model and detailed examination on behavioral and cognitive analysis of potential users including novice engineers and industry practitioners.

Chapter 5 Conclusions and Future Research

This research aimed at formalizing and reusing design coordination knowledge to support resolving spatial conflicts in Mechanical, Electrical, and Plumbing (MEP) systems through systematically gathered design coordination data from past projects. The vision of this research is that the formalized knowledge can be used to provide guidance for early design review incorporating construction considerations, facilitate structured learning from past experience, as well as train novice engineers. This section summarizes the major conclusions and contributions of this research, as well as suggested directions for future research.

5.1 Conclusions and Contributions

This research presents a formalized knowledge representation schema to capture process knowledge in design coordination, which was successfully implemented in a model-based knowledge capture system developed by the author. The knowledge representation schema and the proposed knowledge capture system can be applied in current work practice to improve coordination efficiency while capturing process information in a computer-interpretable manner. The model-based knowledge capture system can store clash information in the form of categorized features and link such categorized information directly to the relevant model elements. It also facilitates organization and management of clashes and supports searching and grouping functions. A prototype system was developed as a plugin to a widely used BIM-based design coordination application and was demonstrated with project data gathered from three new construction projects in the United States. The standardized data was analyzed using data mining techniques for knowledge discovery and reuse. The association-rule technique was applied to identify strong correlations among clash features. Classification models were developed to provide predicted solutions for identified clashes based on historical data. The classification algorithms that produced the best results were selected, which reached precision rates of over 70%. The effectiveness of the classification models was tested in a novice experiment. In the experiment, novice engineers (undergraduate and graduate students in Civil and Architectural Engineering) performed typical coordination tasks (describing a clash and proposing a potential solution) under two conditions: without decision support and with decision support. Their performance in terms of average time spent on each clash and the accuracy (correctness) of the decisions made was evaluated under both conditions. Results show there is significant reduction in time spent by novices to perform coordination tasks with decision support.

This research lends support to construction automation, and in particular, information technology (IT) supported data collection and knowledge acquisition. Future extensions of this research may allow for automated compilation of construction knowledge with reduced reliance on human experts. The proposed approach provides insights on tacit knowledge formalization with data mining techniques and serves as a stepping stone for future development of automated design coordination systems that can apply auto-checking and correction to assist concurrent engineering.

This research also encourages implementing structured lessons learned within/among organizations and achieving constant improvements in project performance. Moreover, it suggests a broader use of BIM – capturing model-related information during design coordination and transferring formalized construction knowledge to early design stages, to next generation construction management professionals, and/or future projects. Expedited design coordination will enable the construction team to concentrate on optimizing construction methods and processes and improving productivity, instead of spending extra time on non-value adding but necessary activities. Formal documentation of the design coordination process and relevant information is highly recommended to industry practitioners. Such documentation allows organizations to reference the database of past constructability issues and solutions during the project or when performing future reviews. The proposed system will also assist construction teams in managing information regarding design coordination issues, as well as lower the cost of data collection and compilation during the analysis.

5.2 Future Research

Knowledge management in the construction industry is a promising research area, especially when integrated with advance information and communication technologies (ICT). Several directions for future research in this area are listed as follows.

(1) Design-construction integration

Fragmentation between design and construction has always been a big concern in the AEC industry. Different methods have been proposed to bridge the information and knowledge silos between design and construction teams, such as promoting meetings between specialty contractors and designers in early design (Gil et al. 2000). Since construction knowledge is largely experience-driven and implicit, it is challenging to transfer such knowledge explicitly and effectively. This research suggests an innovative approach to capture construction knowledge throughout daily work practices and during the problem-solving process. Such approach encourages proactively capturing process information and building the knowledge base without adding too much burden onto practitioners. In other words, the knowledge possessor or processor can at the same time be the knowledge developer for the organization. Consequently, this might lead to the development of advanced knowledge-based computer tools for model checking and revision, which would help designers improve design quality by integrating construction knowledge into design and assisting designers in resolving simple design conflicts. The ultimate goal is to put more emphasis on clash avoidance rather than clash detection (Tommelein and Gholami 2012).

(2) Dynamic reasoning on clashing objects

The reasoning applied in this research is still comparatively static, since it focuses on pair-wise clashes and does not analyze the ripple effects of clashes and changes. It would be interesting to study the relationship and association among clashes. For example, sometimes, moving one object to resolve a clash can lead to a ripple effect of new clashes with other objects, or conversely, can resolve more than one clash at one time. Therefore, the question of how to identify the most efficient way to resolve a clash (i.e. resolving multiple clashes with minimum movements) still remains. Also, what are the impacts of a change in the model in terms of coordination requirements?

When the building information model is linked to additional information repositories, more analysis can be conducted. For example, when the model is linked to a schedule, coordination and construction schedules can be included in the knowledge base to help identify urgent clashes that need to be resolved in a timely manner or automatically rank the level of severity of identified clashes in terms of urgency. When the model is linked to a cost database, cost information can be included in cost-benefit analysis in design coordination.

(3) High-level analysis with increased data

When the size of the database is large enough, we can start studying the effect of different project delivery methods, or project types, or coordination approaches on coordination performance. Project characteristics and team organizations can also influence the design coordination process.

(4) Filtering out false positives

When BIM coordinators conduct clash detection using the automated clash detection tool, a large amount of clashes are reported which are not all relevant. The large amount of irrelevant clashes keeps BIM coordinators from easily finding relevant clashes. Cleaning out false positive and identifying real clashes and critical clashes is a time-consuming task. If BIM coordinators can label clashes found by the software as false and true positives when they are cleaning the output, this information can be gathered and used to improve the reasoning mechanisms of clash detection systems.

(5) Educational effort: problem-based learning using captured project knowledge

There is a significant need to retain tacit knowledge from experienced professional and to use the formalized tacit knowledge in novice training. The proposed knowledge formalization approach provides a less expensive method to capture experiential knowledge. There is still much effort needed in this area to provide better education to future professionals with real world cases and practical training in Problem-Based Learning (PBL) or in other educational settings.

Appendix A – Detailed Descriptions of Use Cases

A.1 Description of the "Create Tag" use case

Use Case Name	Create Tag
Description	User creates a tag by selecting related model elements, inputting tag properties, and saving the above information as a tag. The system verifies the input information and interrelation between the tag and the model and adds the new data item (newly created tag) into the existing tag library.
Actors	User, model, tag library
Preconditions	1. A valid model is open. 2. The "TagPlus" system is successfully loaded.
Post-conditions	1. The tag library is updated with tag information added to the original model file. 2. The displaying color of the tagged model elements changes to yellow.
Normal Flow of Events	1. User selects the model element(s) that he/she wants to tag; 2. User inputs tag information; 3. User submits the request of adding the new tag; 4. "TagPlus" validates the inputs; 5. "TagPlus" saves the tag to the existing tag library and changes the color of the tagged model elements to yellow.
Alternative Flows	1a. User fails to select any model elements; 4a. No model selection is found; 5a. The system sends a warning message saying "No model item is selected" and tag construction fails. 5b. The system sends a warning message saying "No model item is selected" and tag construction fails.

A.2 DESCRIPTION OF THE "DELETE TAG" USE CASE

Use Case Name	Delete Tag
Description	User deletes a tag by selecting the clash ID displayed in the view and click on the delete button. The system verifies one or more tags are selected and removes the selected data items from the existing tag library.
Actors	User, model, tag library
Preconditions	1. A valid model is open. 2. The "TagPlus" system is successfully loaded. 3. One or more tags are selected
Post-conditions	1. The tag library is updated with tag information after removing deleted data items. 2. The displaying colors of the tagged model elements change back to the original colors.
Normal Flow of Events	1. User selects the clashes that he/she wants to delete by selecting their clash IDs; 2. User submits the request of deleting the selected tags by clicking on the delete button; 3. "TagPlus" validates the items to be deleted; 4. "TagPlus" removes the deleted tags in the existing tag library and changes the colors of the untagged model elements back to their original colors.
Alternative Flows	1a. User fails to select any tag; 3a. No tag is seleccted; 4a. The system sends a warning message saying "No tag is selected in the ListView" and tag deletion fails.

A.3 DESCRIPTION OF THE "EDIT TAG" USE CASE

Use Case Name	Edit Tag
Description	User edits the tag properties by selecting one tag, opening the tag properties, editing the information in the form and applying the changes to update the information in the tag library.
Actors	User, model, tag library
Preconditions	1. A valid model is open. 2. The "TagPlus" system is successfully loaded. 3. One and only one tag is selected
Post-conditions	1. The tag library is updated with edited tag information.
Normal Flow of Events	1. User selects the tag that he/she wants to edit and open the tag properties form by clicking on the "Edit Tag" button; 2. "TagPlus" validates the selection; 3. User edits the tag information by changing the input values in the tag properties form; 4a. User applies the changes by clicking on the "Apply" button 4b. Users cancels the action by clicking on the "Cancel" button; 5. "TagPlus" validates the inputs; 6. "TagPlus" saves the edited tag information to the existing tag library.
Alternative Flows	1a. User fails to select any tag; 1b. User selects more than one tag; 2a. The system sends a warning message saying "Please select one tag!" and action fails. 2b. The system sends a warning message saying "Please select only one tag!" and action fails.

A.4 DESCRIPTION OF THE "EDIT OBJECT INFO" USE CASE

Use Case Name	Edit Object Info
Description	User edits the object information of a tagged model component by selecting the model element and inputting object information. The system verifies the input information and adds the object information into the existing tag library.
Actors	User, model, tag library
Preconditions	1. A valid model is open. 2. The "TagPlus" system is successfully loaded. 3. One and only one tagged object is selected.
Post-conditions	1. The tag library is updated with object information added to the original model file.
Normal Flow of Events	1. User selects the tagged object that he/she wants to edit and open the object properties form by clicking on the "Edit Object" button; 2. "TagPlus" validates the selection; 3. User edits the object information by changing the input values in the object properties form; 4. User extracts the geometric information of the object by clicking on the "Read Geometry" button; 5a. User applies the changes by clicking on the "Apply" button 5b. Users ccancels the action by clicking on the "Cancel" button; 6. "TagPlus" validates the inputs; 7. "TagPlus" saves the edited object information to the existing tag library.
Alternative Flows	1a. User fails to select any model elements; 1b. User selects more than one model elements; 1c. User selects one model element without any tag; 2a. The system sends a warning message saying "Please select one object!" and action fails; 2b. The system sends a warning message saying "Please select only one object!" and action fails; 2c. The system sends a warning message saying "The selected model does not exist in any clash tags!" and action fails;

A.5 DESCRIPTION OF THE "SEARCH TAG" USE CASE

Use Case Name	Search Tag
Description	User searches for tags by model, or clash ID or open dates or other clash propertied. The system locates the tags that meet the searching criteria and returns the tag information in the tag viewer window.
Actors	User, model, tag library
Preconditions	1. A valid model is open. 2. The "TagPlus" system is successfully loaded.
Post-conditions	1. The tags that meet the searching criteria are shown in the tag viewer window.
Normal Flow of Events	1. User selects searching category (e.g., model, clash ID, or open date) 2. User inputs searching key word(s) (not needed if search by model) 3. "TagPlus" locates the tags that meet the searching criteria; 4. "TagPlus" displays the tags that meet the searching criteria in the tag viewer window;
Alternative Flows	2. User selects searching by model but fails to select any model element; 3a. The system sends a warning message saying "No model is selected…" and search fails.

A.6 DESCRIPTION OF THE "EXPORT TAG" USE CASE

Use Case Name	Export Tag
Description	User exports the created tags into a text file. The system converts the stored information to a tect file (JSON)
Actors	User, tag library
Preconditions	1. A valid model is open. 2. The "TagPlus" system is successfully loaded. 3. The tag library is not empty.
Post-conditions	1. A text file is generated with the stored tag information.
Normal Flow of Events	1. User clicks on the export option; 2. User selects a folder to locate the exported text file; 3. User executes export; 4. "TagPlus" converts the stored tag information into a text file (JSON) and saves the file to the defined location.

Appendix B – Source Code for the Prototype Plugin Application

B.1 Main Form – Source Code

```
using System;
using System.Collections.Generic;
using System.Windows.Forms;
using System.Text;

//Add two new namespaces
using Autodesk.Navisworks.Api;
using Autodesk.Navisworks.Api.Plugins;
using System.ComponentModel;
using System.Linq;
using System.IO;

using App = Autodesk.Navisworks.Api.Application;

//Add two new namespaces
using Autodesk.Navisworks.Internal;

using Nw = Autodesk.Navisworks.Api;
using Tl = Autodesk.Navisworks.Api.Timeliner;


namespace TagPlusPlugIn
{

    [PluginAttribute("ATagPlusPlugIn",                  //Plugin name
                  "ADSK",                                    //4 character
Developer ID or GUID
                  ToolTip = "TagPlus Plugin",//The tooltip for the item in the
ribbon
                  DisplayName = "TagPlus Plugin")]         //Display name for the
Plugin in the Ribbon

    public class ATagPlusPlugIn : AddInPlugin                    //Derives from
AddInPlugin
    {
        public override int Execute(params string[] parameters)
        {
            mainForm form = mainForm.createMainForm();
            form.Show();
            return 0;
            /*
            //Find the plugin
            PluginRecord pr =

Autodesk.Navisworks.Api.Application.Plugins.FindPlugin("TagPlus.TagPlusDockPane.AD
SK");

            //MessageBox.Show("<1>");
            if (pr != null && pr is DockPanePluginRecord && pr.IsEnabled)
            {
                //check if it needs loading
                if (pr.LoadedPlugin == null)
                {
```

```
                pr.LoadPlugin();
            }

            DockPanePlugin dpp = pr.LoadedPlugin as DockPanePlugin;
            if (dpp != null)
            {
                //switch the Visible flag
                dpp.Visible = !dpp.Visible;
            }
        }
        else
        {
            MessageBox.Show("Missing PlugIn...");
        }

        return 0;
        */
    }
  }
}
```

B.2 New Tag – Source Code

```
using System;
using System.Collections.Generic;
using System.Linq;
using System.Text;
using Autodesk.Navisworks.Api;
using Autodesk.Navisworks.Api.Timeliner;

namespace TagPlusPlugIn
{
    public class Tag
    {
        public const int TAG_FLAG = 0;
        public const int TAG_NAME = 1;
        public const int TAG_OPEN_DATE = 2;
        public const int TAG_CLOSE_DATE = 3;
        public const int TAG_CLASH_TYPE = 4;
        public const int TAG_CLASH_CLAUSE = 5;
        public const int TAG_CLASH_SEVERITY = 6;
        public const int TAG_CLASH_STATUS = 7;
        public const int TAG_SECTION = 8;
        public const int TAG_LEVEL = 9;
        public const int TAG_AREA = 10;
        public const int TAG_ACTIONS = 11;
        public static string[] ACTION_SEPARATORS = new string[] { "[#_ACTION_#]" };
        public const string SIGNITURE = "TAG_PLUS_TAG";

        internal ModelItemCollection models;

        internal string name = "";
        internal string openDate = "";
        internal string closeDate = "";
        internal ClashType clashType = ClashType.Unspecified;
        internal ClashClause clashClause = ClashClause.Unspecified;
        internal ClashSeverity clashSeverity = ClashSeverity.Unspecified;
        internal ClashStatus clashStatus = ClashStatus.Unspecified;

        internal string section = "";
        internal string level = "";
        internal string area = "";

        internal List<Action> actions;

        public Tag()
        {
            models = new ModelItemCollection();
            actions = new List<Action>();
        }

        public Tag(ModelItemCollection ms)
        {
            models = new ModelItemCollection();
            models.AddRange(ms);
            actions = new List<Action>();
        }

        public ModelItemCollection Models
```

```
        {
            get { return models; }
            set { value.CopyTo(models); }
        }

        public List<Action> Actions
        {
            get { return actions; }
            set { actions = new List<Action>(value); }
        }

        //TODO
        public override string ToString()
        {
            return base.ToString();
        }


        public string ToJsonString(Dictionary<ModelItem, TagPlusModelItem>
modelDict)
        {
            StringBuilder res = new StringBuilder();
            res.Append("{");
            res.Append("\"name\":\"" + this.name + "\", ");
            res.Append("\"openDate\":\"" + this.openDate + "\", ");
            res.Append("\"closeDate\":\"" + this.closeDate + "\", ");
            res.Append("\"clashType\":\"" + this.clashType.ToString() + "\", ");
            res.Append("\"clashClause\":\"" + this.clashClause.ToString() + "\",
");
            res.Append("\"clashSeverity\":\"" + this.clashSeverity.ToString() +
"\", ");
            res.Append("\"clashStatus\":\"" + this.clashStatus.ToString() + "\",
");
            res.Append("\"section\":\"" + this.section + "\", ");
            res.Append("\"level\":\"" + this.level + "\", ");
            res.Append("\"area\":\"" + this.area + "\", ");

            res.Append("\"models\":");
            res.Append("[");
            for (int i = 0; i < this.models.Count - 1; i++)
            {
                TagPlusModelItem tagModel = modelDict[this.models[i]];
                res.Append(tagModel.ToJsonString() + ", ");
            }
            res.Append(modelDict[this.models[this.models.Count -
1]].ToJsonString());
            res.Append("], ");

            res.Append("\"actions\":");
            res.Append("[");
            for (int i = 0; i < this.actions.Count - 1; i++)
            {
                res.Append(actions[i].ToJsonString() + ", ");
            }
            res.Append(this.actions[this.actions.Count - 1].ToJsonString());
            res.Append("]");

            res.Append("}");
```

```
            return res.ToString();
        }

        public static Tag copyFromTimelinerTask(TimelinerTask tTask)
        {
            if (tTask.Comments.Count == 0)
            {
                return null;
            }
            if
(!tTask.Comments[Tag.TAG_FLAG].Body.ToString().Equals(Tag.SIGNITURE))
            {
                return null;
            }
            if (!tTask.Selection.HasExplicitSelection)
            {
                return null;
            }
            Tag res = new Tag();
            res.models.CopyFrom(tTask.Selection.ExplicitSelection);

            res.name = tTask.Comments[Tag.TAG_NAME].Body;
            res.openDate = tTask.Comments[Tag.TAG_OPEN_DATE].Body;
            res.closeDate = tTask.Comments[Tag.TAG_CLOSE_DATE].Body;
            res.clashType = (ClashType)Enum.Parse(typeof(ClashType),
tTask.Comments[Tag.TAG_CLASH_TYPE].Body);
            res.clashClause = (ClashClause)Enum.Parse(typeof(ClashClause),
tTask.Comments[Tag.TAG_CLASH_CLAUSE].Body);
            res.clashSeverity = (ClashSeverity)Enum.Parse(typeof(ClashSeverity),
tTask.Comments[Tag.TAG_CLASH_SEVERITY].Body);
            res.clashStatus = (ClashStatus)Enum.Parse(typeof(ClashStatus),
tTask.Comments[Tag.TAG_CLASH_STATUS].Body);
            res.section = tTask.Comments[Tag.TAG_SECTION].Body;
            res.level = tTask.Comments[Tag.TAG_LEVEL].Body;
            res.area = tTask.Comments[Tag.TAG_AREA].Body;
            string[] actionStrings =
tTask.Comments[Tag.TAG_ACTIONS].Body.Split(Tag.ACTION_SEPARATORS,
StringSplitOptions.RemoveEmptyEntries);
            foreach (string s in actionStrings)
            {
                res.actions.Add(new Action(s));
            }
            return res;
        }

        private Comment createComment(string comment)
        {
            Comment c = new Comment(comment, CommentStatus.Active);
            return c;
        }

        public TimelinerTask convertToTimeLinerTask()
        {
            TimelinerTask t = new TimelinerTask();

            t.Selection.CopyFrom(this.models);

            Comment c = null;
```

```
            c = createComment(Tag.SIGNITURE);
            t.Comments.Add(c);

            c = createComment(this.name);
            t.Comments.Add(c);

            c = createComment(this.openDate);
            t.Comments.Add(c);

            c = createComment(this.closeDate);
            t.Comments.Add(c);

            c = createComment(this.clashType.ToString());
            t.Comments.Add(c);

            c = createComment(this.clashClause.ToString());
            t.Comments.Add(c);

            c = createComment(this.clashSeverity.ToString());
            t.Comments.Add(c);

            c = createComment(this.clashStatus.ToString());
            t.Comments.Add(c);

            c = createComment(this.section);
            t.Comments.Add(c);

            c = createComment(this.level);
            t.Comments.Add(c);

            c = createComment(this.area);
            t.Comments.Add(c);

            StringBuilder actionsComment = new StringBuilder();
            if (actions.Count > 0)
            {
                actionsComment.Append(actions[0].ToString());
            }
            for (int i = 0; i < actions.Count; i++)
            {
                actionsComment.Append(Tag.ACTION_SEPARATORS[0]);
                actionsComment.Append(actions[i].ToString());
            }

            c = createComment(actionsComment.ToString());
            t.Comments.Add(c);

            return t;
        }

    }

    public class TagList : ISubject
    {
        internal List<IObserver> obList;
        internal Dictionary<string, Tag> tagsByName = new Dictionary<string,
Tag>();
```

```
public List<Tag> FindAll(Predicate<Tag> match)
{
    Dictionary<string, Tag>.ValueCollection tags = tagsByName.Values;
    List<Tag> result = new List<Tag>();
    foreach (Tag t in tags)
    {
        if (match.Invoke(t))
        {
            result.Add(t);
        }
    }
    return result;
}

public Tag getTag(string id)
{
    if (tagsByName.ContainsKey(id))
    {
        return tagsByName[id];
    }
    return null;
}

public void Remove(Tag t)
{
    if (tagsByName.ContainsKey(t.name))
    {
        tagsByName.Remove(t.name);
    }
}


public bool ifNameConflict(string newName)
{
    return tagsByName.ContainsKey(newName);
}

public int Count
{
    get { return tagsByName.Count; }
}


public void Add(Tag t)
{
    tagsByName.Add(t.name, t);
}


public void Clear()
{
    tagsByName.Clear();
}

public TagList()
    : base()
{
```

```
            obList = new List<IObserver>();
        }

        // Subject/Observer Pattern
        void ISubject.RegisterObserver(IObserver ob)
        {
            obList.Add(ob);
        }

        void ISubject.RemoveObserver(IObserver ob)
        {
            obList.Remove(ob);
        }

        void ISubject.NotifyObserver()
        {
            foreach (IObserver ob in obList)
            {
                ob.update(this);
            }
        }
    }

    public class TagPlusModelItem
    {
        public const int FLAG_FIELD = 0;
        public const int DISCIPLINE_FIELD = 1;
        public const int IS_CRITICAL_FIELD = 2;
        public const int COMPONENT_FIELD = 3;
        public const int AREA_FIELD = 4;
        public const int LEN_FIELD = 5;
        public const int ELEVATION_FIELD = 6;
        public const int SLOPE_FIELD = 7;
        public const int COUNT_FIELD = 8;
        public const string SIGNITURE = "TAG_PLUS_MODEL_ITEM";

        internal ModelItem originalModel = null;
        internal Trade discipline = Trade.Unspecified;
        internal bool isCritical = false;
        internal string component = "";
        internal double area = -1;
        internal double len = -1;
        internal string elevation = "";
        internal double slope = -1;
        internal double weight = -1;

        public TagPlusModelItem(ModelItem m)
        {
            this.originalModel = m;
        }

        //TODO
        public override string ToString()
        {
            return base.ToString();
        }

        public string ToJsonString()
```

```
        {
            StringBuilder res = new StringBuilder();
            res.Append("{");
            res.Append("\"discipline\":\"" + this.discipline.ToString() + "\", ");
            res.Append("\"component\":\"" + this.component + "\", ");
            res.Append("\"area\":\"" + this.area.ToString() + "\", ");
            res.Append("\"len\":\"" + this.len.ToString() + "\", ");
            res.Append("\"elevation\":\"" + this.elevation.ToString() + "\", ");
            res.Append("\"slope\":\"" + this.slope.ToString() + "\", ");
            res.Append("\"weight\":\"" + this.weight.ToString() + "\"");
            res.Append("}");
            return res.ToString();
        }

        public static TagPlusModelItem copyFromTimelinerTask(TimelinerTask t)
        {
            if (t.Comments.Count == 0)
            {
                return null;
            }
            if
(!t.Comments[TagPlusModelItem.FLAG_FIELD].Body.ToString().Equals(TagPlusModelItem.
SIGNITURE))
            {
                return null;
            }
            if (!t.Selection.HasExplicitSelection)
            {
                return null;
            }
            TagPlusModelItem res = new
TagPlusModelItem(t.Selection.ExplicitSelection[0]);
            res.discipline = (Trade)Enum.Parse(typeof(Trade),
t.Comments[TagPlusModelItem.DISCIPLINE_FIELD].Body);
            res.isCritical =
Boolean.Parse(t.Comments[TagPlusModelItem.IS_CRITICAL_FIELD].Body);
            res.component = t.Comments[TagPlusModelItem.COMPONENT_FIELD].Body;
            res.area = Double.Parse(t.Comments[TagPlusModelItem.AREA_FIELD].Body);
            res.len = Double.Parse(t.Comments[TagPlusModelItem.LEN_FIELD].Body);
            res.elevation = t.Comments[TagPlusModelItem.ELEVATION_FIELD].Body;
            res.slope =
Double.Parse(t.Comments[TagPlusModelItem.SLOPE_FIELD].Body);
            res.weight =
double.Parse(t.Comments[TagPlusModelItem.COUNT_FIELD].Body);
            return res;
        }

        private Comment createComment(string comment)
        {
            Comment c = new Comment(comment, CommentStatus.Active);
            return c;
        }

        public TimelinerTask convertToTimelinerTask()
        {
            TimelinerTask t = new TimelinerTask();
            ModelItemCollection models = new ModelItemCollection();
            models.Add(this.originalModel);
```

```
            t.Selection.CopyFrom(models);

            Comment c = null;

            c = createComment(TagPlusModelItem.SIGNITURE);
            t.Comments.Add(c);

            c = createComment(this.discipline.ToString());
            t.Comments.Add(c);

            c = createComment(this.isCritical.ToString());
            t.Comments.Add(c);

            c = createComment(this.component);
            t.Comments.Add(c);

            c = createComment(this.area.ToString());
            t.Comments.Add(c);

            c = createComment(this.len.ToString());
            t.Comments.Add(c);

            c = createComment(this.elevation.ToString());
            t.Comments.Add(c);

            c = createComment(this.slope.ToString());
            t.Comments.Add(c);

            c = createComment(this.weight.ToString());
            t.Comments.Add(c);

            return t;
        }

    }

    public enum ClashType { Unspecified, Hard, Barely_Clipping, Clearance, Soft };
    public enum ClashClause { Unspecified, Design_Issue, Modeling_Issue };
    public enum ClashSeverity { Unspecified, High, Medium, Low, None };
    public enum ClashStatus { Unspecified, Active, Hold, Resolved, Ignored };
    public enum Trade { Unspecified, Mechanical, Electrical, Plumbing,
Fire_Protection };

    public class Action
    {
        internal Trade trade = Trade.Unspecified;
        internal string action = "";
        internal string dueDate = "";
        internal string constraints = "";

        public static string[] SEPARATORS = new string[] { "[#_ACTION_FIELDS_#]" };

        public Action()
        {
            return;
        }

        public Action(String s)
```

```
        {
            string[] values = s.Split(SEPARATORS, StringSplitOptions.None);
            trade = (Trade)Enum.Parse(typeof(Trade), values[0]);
            action = values[1];
            dueDate = values[2];
            constraints = values[3];
        }

        public override string ToString()
        {
            return trade + SEPARATORS[0] + action + SEPARATORS[0] + dueDate +
SEPARATORS[0] + constraints;
        }

        public string ToJsonString()
        {
            StringBuilder res = new StringBuilder();
            res.Append("{");
            res.Append("\"trade\":\"" + this.trade.ToString() + "\", ");
            res.Append("\"action\":\"" + this.action + "\", ");
            res.Append("\"dueDate\":\"" + this.dueDate + "\", ");
            res.Append("\"constraints\":\"" + this.constraints + "\"");
            res.Append("}");
            return res.ToString();
        }
    }
}
```

B.3 TagPropertyForm– Source Code

```
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Drawing;
using System.Linq;
using System.Text;
using System.Windows.Forms;

namespace TagPlusPlugIn
{
    public partial class TagPropertyForm : Form
    {
        Tag underlyingTag = null;
        mainForm parentForm = null;
        TagList allTags = null;
        List<Action> actions = null;
        public TagPropertyForm(Tag tag, mainForm mForm, TagList parentAllTags)
        {
            InitializeComponent();
            addDataSource();
            underlyingTag = tag;
            parentForm = mForm;
            this.allTags = parentAllTags;
            actions = new List<Action>();
            actions.AddRange(underlyingTag.actions);
            displayTagProperties();

            Location = new Point(parentForm.Location.X, parentForm.Location.Y);
            TopMost = true;
        }

        public void displayTagProperties()
        {
            clashIDBox.Text = underlyingTag.name;
            sectionBox.Text = underlyingTag.section;
            areaBox.Text = underlyingTag.area;
            levelBox.Text = underlyingTag.level;
            clashTypeBox.SelectedIndex = 
clashTypeBox.FindStringExact(underlyingTag.clashType.ToString());
            clashCauseBox.SelectedIndex = 
clashCauseBox.FindStringExact(underlyingTag.clashClause.ToString());
            clashSeverityBox.SelectedIndex = 
clashSeverityBox.FindStringExact(underlyingTag.clashSeverity.ToString());
            clashStatusBox.SelectedIndex = 
clashStatusBox.FindStringExact(underlyingTag.clashStatus.ToString());
            try
            {
                openDateBox.Value = DateTime.Parse(underlyingTag.openDate);
                closeDateBox.Value = DateTime.Parse(underlyingTag.closeDate);
            }
            catch(Exception)
            {
               // MessageBox.Show(ex.Message);
            }
```

```
            displayActions();
        }
        public void addDataSource()
        {
            clashTypeBox.DataSource =
Enum.GetValues(typeof(TagPlusPlugIn.ClashType));
            clashCauseBox.DataSource =
Enum.GetValues(typeof(TagPlusPlugIn.ClashClause));
            clashSeverityBox.DataSource =
Enum.GetValues(typeof(TagPlusPlugIn.ClashSeverity));
            clashStatusBox.DataSource =
Enum.GetValues(typeof(TagPlusPlugIn.ClashStatus));
            tradeBox.DataSource = Enum.GetValues(typeof(TagPlusPlugIn.Trade));
        }

        private void cancelButton_Click(object sender, EventArgs e)
        {
            Close();
        }

        private void applyButton_Click(object sender, EventArgs e)
        {
            if (allTags.tagsByName.ContainsKey(clashIDBox.Text.ToString()))
            {
                MessageBox.Show("Clash ID: " + clashIDBox.Text.ToString() + " has
already exits!");
            }
            else
            {
                underlyingTag.name = clashIDBox.Text.ToString();
                underlyingTag.section = sectionBox.Text.ToString();
                underlyingTag.area = areaBox.Text.ToString();
                underlyingTag.level = levelBox.Text.ToString();
                underlyingTag.clashType = (ClashType)Enum.Parse(typeof(ClashType),
clashTypeBox.SelectedValue.ToString());
                underlyingTag.clashClause =
(ClashClause)Enum.Parse(typeof(ClashClause),
clashCauseBox.SelectedValue.ToString());
                underlyingTag.clashSeverity =
(ClashSeverity)Enum.Parse(typeof(ClashSeverity),
clashSeverityBox.SelectedValue.ToString());
                underlyingTag.clashStatus =
(ClashStatus)Enum.Parse(typeof(ClashStatus),
clashStatusBox.SelectedValue.ToString());
                underlyingTag.openDate = openDateBox.Value.Date.ToString();
                underlyingTag.closeDate = closeDateBox.Value.Date.ToString();
                underlyingTag.actions.Clear();
                underlyingTag.actions.AddRange(actions);
                Close();
            }
        }

        private void button1_Click(object sender, EventArgs e)
        {
            Action a = new Action();
            a.action = actionBox.Text.ToString();
            a.trade = (Trade)Enum.Parse(typeof(Trade),
tradeBox.SelectedValue.ToString());
```

```
            a.dueDate = dueDateBox.Value.Date.ToString();
            a.constraints = constraintsBox.Text.ToString();
            actions.Add(a);
            displayActions();
        }

        public void displayActions()
        {
            actionList.Items.Clear();
            foreach(Action a in actions)
            {
                ListViewItem listItem = new ListViewItem();
                listItem.Text = a.trade.ToString();
                listItem.SubItems.Add(a.action);
                listItem.SubItems.Add(a.dueDate);
                listItem.SubItems.Add(a.constraints);
                actionList.Items.Add(listItem);
            }
        }

        private void deleteAction_Click(object sender, EventArgs e)
        {
            if(actionList.SelectedItems.Count == 0)
            {
                MessageBox.Show("Please select one action item!");
            }
            else if (actionList.SelectedItems.Count > 1)
            {
                MessageBox.Show("Please select only one action item at a time!");
            }
            else
            {
                actions.RemoveAt(actionList.SelectedIndices[0]);
                displayActions();
            }
        }

    }
}
```

B.4 ObjectPropertyForm– Source Code

```
using System;
using System.Collections.Generic;
using System.ComponentModel;
using System.Data;
using System.Drawing;
using System.Linq;
using System.Text;
using System.Windows.Forms;
using Autodesk.Navisworks.Api;

namespace TagPlusPlugIn
{
    public partial class ObjectPropertyForm : Form
    {
        TagPlusModelItem underlyingModel = null;
        List<String> geometryInfo = null;
        bool isFirstTime = false;
        public ObjectPropertyForm(TagPlusModelItem model, mainForm parentForm)
        {
            InitializeComponent();
            underlyingModel = model;
            isFirstTime = (model.discipline == Trade.Unspecified);
            geometryInfo = new List<string>();
            addDataSource();
            Location = new Point(parentForm.Location.X, parentForm.Location.Y);
            TopMost = true;
            if (!isFirstTime)
            {
                displayGeometryInfo();
                tradeBox.SelectedIndex =
tradeBox.FindStringExact(underlyingModel.discipline.ToString());
                componentBox.Text = underlyingModel.component;
                if(underlyingModel.isCritical)
                {
                    criticalYes.Checked = true;
                    criticalNo.Checked = false;
                }
                else
                {
                    criticalNo.Checked = true;
                    criticalYes.Checked = false;
                }
            }
        }

        public void addDataSource()
        {
            tradeBox.DataSource = Enum.GetValues(typeof(TagPlusPlugIn.Trade));
        }


        public void displayGeometryInfo()
        {
            geometryInfo.Clear();
            if (Math.Abs(underlyingModel.area + 1) < 0.00001)
            {
```

```
                geometryInfo.Add("Area: N/A");
            }
            else
            {
                geometryInfo.Add("Area: " + underlyingModel.area);
            }

            if (Math.Abs(underlyingModel.len + 1) < 0.00001)
            {
                geometryInfo.Add("Length: N/A");
            }
            else
            {
                geometryInfo.Add("Length: " + underlyingModel.len);
            }


            if (underlyingModel.elevation.Equals(""))
            {
                geometryInfo.Add("Evaluation: N/A");
            }
            else
            {
                geometryInfo.Add("Evaluation: " + underlyingModel.elevation);
            }


            if (Math.Abs(underlyingModel.slope + 1) < 0.00001)
            {
                geometryInfo.Add("Slope: N/A");
            }
            else
            {
                geometryInfo.Add("Slope: " + underlyingModel.slope);
            }


            if (Math.Abs(underlyingModel.weight + 1) < 0.00001)
            {
                geometryInfo.Add("Weight: N/A");
            }
            else
            {
                geometryInfo.Add("Weight: " + underlyingModel.weight);
            }
            GeometryInfoList.DataSource = null;
            GeometryInfoList.DataSource = geometryInfo;
        }


        public void readGeometryInfo()
        {
            try
            {
                foreach(PropertyCategory pc in
underlyingModel.originalModel.PropertyCategories)
                {
                    if (!pc.Name.Equals("MAPS_SOLID"))
```

```
                    {
                        continue;
                    }

                    foreach (DataProperty dp in pc.Properties)
                    {
                        if (dp.Name.Equals("Area[0]"))
                        {
                            if (dp.Value.IsAnyDouble)
                            {
                                underlyingModel.area = dp.Value.ToAnyDouble();
                            }
                            else
                            {
                                MessageBox.Show("Unrecognized Area type: " +
dp.Value.ToString());
                            }
                        }
                        else if (dp.Name.Equals("LengthAngle[0]"))
                        {
                            if (dp.Value.IsAnyDouble)
                            {
                                underlyingModel.len = dp.Value.ToAnyDouble();
                            }
                            else
                            {
                                MessageBox.Show("Unrecognized Length type: " +
dp.Value.ToString());
                            }
                        }
                        else if (dp.Name.Equals("Weight[0]"))
                        {
                            if (dp.Value.IsAnyDouble)
                            {
                                underlyingModel.weight = dp.Value.ToAnyDouble();
                            }
                            else
                            {
                                MessageBox.Show("Unrecognized Weight type: " +
dp.Value.ToString());
                            }
                        }
                        else if (dp.Name.Equals("Elevation[0]"))
                        {
                            if (dp.Value.IsDisplayString)
                            {
                                underlyingModel.elevation =
dp.Value.ToDisplayString();
                            }
                            else
                            {
                                MessageBox.Show("Unrecognized Elevation type: " +
dp.Value.ToString());
                            }
                        }

                    }
                }
```

```
            }
            catch(Exception ex)
            {
                MessageBox.Show(ex.Message);
            }
        }

        private void tradeBox_SelectedIndexChanged(object sender, EventArgs e)
        {
            underlyingModel.discipline = (Trade)Enum.Parse(typeof(Trade),
tradeBox.SelectedValue.ToString());
        }

        private void componentBox_TextChanged(object sender, EventArgs e)
        {
            underlyingModel.component = componentBox.Text;
        }

        private void criticalNo_CheckedChanged(object sender, EventArgs e)
        {
            if (criticalNo.Checked == true)
            {
                underlyingModel.isCritical = false;
            }
            else
            {
                underlyingModel.isCritical = true;
            }
        }

        private void CriticalYes_CheckedChanged(object sender, EventArgs e)
        {
            if (criticalYes.Checked == true)
            {
                underlyingModel.isCritical = true;
            }
            else
            {
                underlyingModel.isCritical = false;
            }
        }

        private void tradeBox_SelectionChangeCommitted(object sender, EventArgs e)
        {
            underlyingModel.discipline = (Trade)Enum.Parse(typeof(Trade),
tradeBox.SelectedValue.ToString());
        }

        private void readGeoButton_Click(object sender, EventArgs e)
        {
            readGeometryInfo();
            displayGeometryInfo();
        }
    }
}
```

Appendix C – Clash Database

Ver.	ID	Lvl	Trade	Object	Direction	Cause	Clash Type	Open Date	Close Date	Resolution Duration (days)	Res.Trade	Res. Object	No. of Trades	No. of Clashing Objects	Action
1	101	0	AP	COL-STM	V-V	Modeling Error	Hard	6/5/2012	6/12/2012	7	P	STM	2	2	Move
1	102	0	AP	COL-STM	V-V	Modeling Error	Hard	6/5/2012	6/12/2012	7	P	STM	2	2	Move
1	103	0	PS	STM-SLAB	H-H	Modeling Error	Hard	6/5/2012	6/19/2012	14	P	STM	2	2	Lower
1	104	0	PS	STM-PIER	V-V	Modeling Error	Hard	6/5/2012	6/12/2012	7	P	STM	2	2	Remove
1	105	0	PS	SAN,DCW-FNDN	H-H(X)	Modeling Error	Hard	6/5/2012	6/19/2012	14	P,S	SAN,DCW_FNDN	2	3	Remove_Lower_Raise
1	106	0	PS	SAN-SLAB	V-H	Modeling Error	Hard	6/5/2012	6/12/2012	7	P	SAN	2	2	Reroute
1	107	0	PS	STM-PIER	H-V	Modeling Error	Barely Clipping	6/5/2012	6/12/2012	7	P	STM	2	5	Move
1	108	0	AP	SPACE-SAN	S-V	Modeling Error	Soft	6/5/2012	6/12/2012	7	P	SAN	2	1	Reroute
1	109	0	AP	WALL-SAN	V-V	Modeling Error	Barely Clipping	6/5/2012	6/12/2012	7	P	SAN	2	2	Reshape
1	110	0	PS	STM-PIER	H-V	Modeling Error	Barely Clipping	6/5/2012	6/12/2012	7	P	STM	2	2	Move
1	111	0	PS	SAN-PIER	V-V	Modeling Error	Hard	6/5/2012	6/12/2012	7	P	SAN	2	2	Reroute
1	112	0	PS	SAN-PIER	V-V	Modeling	Barely	6/5/2012	6/19/2012	14	P	SAN	2	2	Move

						Error	Clipping								
1	114	0	ES	GRD-FNDN	V-H	Modeling Error	Hard	6/5/2012	6/12/2012	7	E	GRD	2	3	Raise
1	115	0	SU	PIER-UPIPE	V-H	Modeling Error	Barely Clipping	6/5/2012	6/5/2012	0	N/A	N/A	2	2	Ignore
1	117	0	EP	PWR-STM	H-H(X)	Coordinatio n Issue	Barely Clipping	6/5/2012	6/12/2012	7	E	PWR	2	5	Lower
1	118	0	EP	PWR-SAN	H-V	Coordinatio n Issue	Barely Clipping	6/5/2012	6/12/2012	7	E	PWR	2	2	Lower
1	119	0	EU	PWR-USTRUC	H-V	Modeling Error	Barely Clipping	6/5/2012	6/12/2012	7	E	PWR	2	2	Reroute
1	120	0	EU	DAT-UCOND	H-H(X)	Modeling Error	Barely Clipping	6/5/2012	6/12/2012	7	E	DAT	2	4	Lower
2	201	0	PS	SAN-FNDN	H-H(X)	Design Issue	Barely Clipping	6/12/2012	6/19/2012	7	S	FNDN	2	2	Reshap e
2	203	0	PS	SAN-SLAB	V-H	Modeling Error	Hard	6/12/2012	6/19/2012	7	P	SAN	2	2	Lower
2	204	0	ES	PWR-FNDN	H-H(X)	Modeling Error	Barely Clipping	6/12/2012	6/19/2012	7	E	PWR	2	5	Lower
2	205	0	ES	PWR-FNDN	H-H(X)	Modeling Error	Barely Clipping	6/12/2012	6/19/2012	7	S	FNDN	2	5	Reshap e
3	301	0	S	SECTION	H	Modeling Error	Soft	6/19/2012	8/21/2012	63	S	SECTION	1	1	Update
3	302	0	S	PIER	H	Modeling Error	Soft	6/19/2012	8/21/2012	63	S	PIER	1	1	Update
3	303	0	S	PIER	H	Modeling Error	Soft	6/19/2012	8/21/2012	63	S	PIER	1	1	Update
3	304	0	S	SLAB	H	Modeling Error	Soft	6/19/2012	8/21/2012	63	S	SLAB	1	1	Update
3	305	0	S	PIER	H	Modeling Error	Soft	6/19/2012	8/21/2012	63	S	PIER	1	1	Update
3	306	0	FS	EQUIP-SLAB	H-H	Modeling Error	Hard	6/19/2012	8/21/2012	63	F	EQUIP	2	2	Raise
3	307	0	FS	BRANCH-	H-	Modeling	Hard	6/19/2012	9/4/2012	77	F	BRANCH	2	2	Remove

				STLB	H(X)	Error									
3	308	0	FS	MAIN-STLB	H-H	Modeling Error	Hard	6/19/2012	8/21/2012	63	F	MAIN	2	2	Lower
3	309	0	FS	MAIN-STLB	H-H(X)	Modeling Error	Barely Clipping	6/19/2012	8/14/2012	56	F	MAIN	2	2	Lower
13	401	1	MP	D'MPSA-SAN	H-H	Coordination Issue	Hard	8/21/2012	8/27/2012	6	P	SAN	2	4	Reroute
13	402	1	FM	DROP-R'MPSA	V-H	Modeling Error	Hard	8/21/2012	9/4/2012	14	F	DROP	2	2	Move
13	403	1	AP	SPACE-STM	S-V	Modeling Error	Soft	8/21/2012	9/4/2012	14	P	STM	2	1	Move
13	403	1	PS	STM-STLB	H-H	Modeling Error	Hard	8/21/2012	9/4/2012	14	P	STM	2	2	Lower
13	404	1	AP	SPACE-STM	S-V	Modeling Error	Soft	8/21/2012	8/27/2012	6	P	STM	2	1	Remove
13	405	1	AP	WALL-NGAS	V-V	Modeling Error	Hard	8/21/2012	8/27/2012	6	P	NGAS	2	2	Move
13	405	1	AP	WALL-STM	V-V	Modeling Error	Hard	8/21/2012	9/4/2012	14	A	WALL	2	2	Reshape
13	406	1	A	CLG	H	Design Issue	Soft	8/21/2012	8/27/2012	6	A	CLG	1	1	Verify
13	407	1	AM	CLG-R'LPSA	H-H	Modeling Error	Hard	8/21/2012	8/27/2012	6	M	R'LPSA	2	2	Reroute
13	408	1	AM	CLG-R'LPSA	H-H	Modeling Error	Hard	8/21/2012	8/27/2012	6	M	R'LPSA	2	2	Raise
14	408	1	AP	WALL-SAN	V-H	Modeling Error	Hard	8/21/2012	8/27/2012	6	P	SAN	2	2	Raise
13	409	1	AE	CLG-LGT	H-V	Modeling Error	Hard	8/21/2012	8/27/2012	6	E	LGT	2	2	Remove
13	410	1	AE	CLG-LGT	H-V	Modeling Error	Hard	8/21/2012	8/27/2012	6	E	LGT	2	2	Remove
13	411	1	MM	VAV-GRL	V-V	Modeling Error	Clearance	8/21/2012	8/27/2012	6	M	GRL	2	1	Move
14	501	1	MS	GRL-STLB	V-H	Modeling Error	Hard	8/27/2012	9/4/2012	8	M	GRL	2	2	Move

14	502	1	MS	EL'LPSA-STLB	V-H	Modeling Error	Barely Clipping	8/27/2012	9/4/2012	8	M	EL'LPSA	2	2	Move
14	503	1	MS	SEL'LPRA-STLC	H-V	Modeling Error	Barely Clipping	8/27/2012	9/4/2012	8	M	SEL'LPRA	2	2	Move
14	504	1	PS	NGAS-STLCONN	H-V	Modeling Error	Hard	8/27/2012	9/4/2012	8	P	NGAS	2	2	Reroute
14	505	1	PS	DHW-STLCONN	H-V	Modeling Error	Hard	8/27/2012	9/4/2012	8	P	DHW	2	2	Move
14	506	1	PS	SAN-STLB	H-H(X)	Modeling Error	Hard	8/27/2012	9/4/2012	8	P	SAN	2	2	Reroute
14	507	1	PS	VAL-STLC	H-V	Modeling Error	Hard	8/27/2012	9/4/2012	8	P	VAL	2	2	Remove
14	509	1	FS	BRANCH-STLC	V-H	Modeling Error	Barely Clipping	8/27/2012	9/4/2012	8	F	BRANCH	2	2	Reroute
14	509	1	FS	BRANCH-STLBRACE	H-V	Modeling Error	Barely Clipping	8/27/2012	9/26/2012	30	F	BRANCH	2	2	Raise
14	510	1	AP	SPACE-STM	S-V	Modeling Error	Soft	8/27/2012	9/4/2012	8	P	STM	2	1	Move
14	511	1	AM	CLG-D'LPSA	H-H	Coordination Issue	Hard	8/27/2012	9/4/2012	8	M	D'LPSA	2	2	Raise
14	511	1	EM	LGT-D'LPSA	H-H(X)	Coordination Issue	Hard	8/27/2012	9/4/2012	8	M	D'LPSA	2	2	Raise
14	512	1	AM	CLG-MDUCT	H-H	Modeling Error	Hard	8/27/2012	9/4/2012	8	M	MDUCT	2	20	Raise
14	513	1	AM	CLG-MDUCT	H-H	Modeling Error	Hard	8/27/2012	9/4/2012	8	M	MDUCT	2	20	Raise
14	514	1	AM	CLG-R'LPSA,GRL	H-H,V	Modeling Error	Hard	8/27/2012	9/4/2012	8	M	R'LPSA_GRL	2	3	Raise
14	515	1	AM	CLG-D'MPSA	H-H	Coordination Issue	Hard	8/27/2012	9/4/2012	8	M	D'MPSA	2	2	Reshape Reroute
14	515	1	FM	BRANCH-D'MPSA	H-H	Coordination Issue	Hard	8/27/2012	9/4/2012	8	F	BRANCH	2	2	Reroute
14	516	1	AP	CLG-SAN	H-H	Coordinatio	Barely	8/27/2012	9/4/2012	8	P	SAN	2	2	Reroute

						n Issue	Clipping								
14	517	1	AP	SPACE-DCW	S-V	Modeling Error	Soft	8/27/2012	9/4/2012	8	P	DCW	2	1	Move
14	518	1	AP	CLG-SAN	H-H	Modeling Error	Hard	8/27/2012	9/4/2012	8	P	SAN	2	2	Raise
15	601	1	MS	FLEX'LPSA-STLB	H-H(X)	Modeling Error	Barely Clipping	8/30/2012	11/12/2012	74	M	FLEX'LPSA	2	2	Move
15	612	1	EM	LGT-R'LPSA	H-H(X)	Coordination Issue	Hard	8/30/2012	9/4/2012	5	M	R'LPSA	2	2	Raise
15	617	1	EM	LGT-GRL	H-H	Coordination Issue	Hard	8/30/2012	9/4/2012	5	M	GRL	2	4	Move
15	618	1	EM	LGT-D'LPSA	H-H	Coordination Issue	Barely Clipping	8/30/2012	9/4/2012	5	M(F)	D'LPSA(3 BRANCH)	2	9	Raise(3Lower)
15	619	1	FM	BRANCH-D'MPSA	V-H	Coordination Issue	Barely Clipping	8/30/2012	9/7/2012	8	F	BRANCH	2	2	Move
15	620	1	EM	LGT-GRL	H-H	Coordination Issue	Hard	8/30/2012	9/4/2012	5	M	GRL	2	2	Move
16	701	1	PS	DCW-STLCONN	H-V	Modeling Error	Hard	9/5/2012	9/7/2012	2	P	DCW	2	2	Move
16	702	1	AP	FRM-STM	V-H	Design Issue	Barely Clipping	9/5/2012	9/7/2012	2	A	FRM	2	2	Verify
16	703	1	FS	MAIN-STLB	H-H(X)	Coordination Issue	Barely Clipping	9/5/2012	9/7/2012	2	F	MAIN	2	2	Lower
16	704	1	EM	CHWS-CHWR	H-H(X)	Modeling Error	Hard	9/5/2012	11/12/2012	68	E	CHWS	2	2	Remove
16	705	1	EF	HNGR-BRANCH	H-H(X)	Coordination Issue	Barely Clipping	9/5/2012	9/7/2012	2	E	HNGR	2	2	Move
16	706	1	EF	CON-BRANCH	H-H(X)	Coordination Issue	Barely Clipping	9/5/2012	9/7/2012	2	E	CON	2	2	Raise
16	707	1	EF	CON-BRANCH	H-H(X)	Coordination Issue	Barely Clipping	9/5/2012	9/7/2012	2	E	CON	2	3	Raise
16	708	1	EF	CON-BRANCH	H-H(X)	Coordination Issue	Hard	9/5/2012	9/7/2012	2	E	CON	2	2	Bend Lower
16	709	1	EP	HNGR-SAN	H-	Coordinatio	Barely	9/5/2012	9/7/2012	2	E	CON	2	2	Move

					H(X)	n Issue	Clipping								
16	710	1	FP	BRANCH- DHW,DCW	H- H(X)	Coordinatio n Issue	Barely Clipping	9/5/2012	9/7/2012	2	F	BRANCH	2	4	Lower
16	711	1	FP	DROP-DCW	V-H	Coordinatio n Issue	Barely Clipping	9/5/2012	9/7/2012	2	F,P	DCW,BR ANCH	2	2	Move_L ower
16	712	1	F M	BRANCH- CHWS	H-V	Coordinatio n Issue	Barely Clipping	9/5/2012	9/26/2012	21	F,P	BRANCH, CHWS	2	2	Raise_L ower
16	713	1	EP	LGT-DCW	V-H	Coordinatio n Issue	Hard	9/5/2012	9/7/2012	2	P	DCW	2	2	Raise
16	714	1	E M	LGT-FCU	H-H	Coordinatio n Issue	Barely Clipping	9/5/2012	11/12/2012	68	M	FCU	2	2	Move
16	715	1	E M	HNGR- D'MPSA	H-H	Coordinatio n Issue	Clearanc e	9/5/2012	9/7/2012	2	E	HNGR	2	1	Move
16	716	1	E M	CON- R'LPSA	H- H(X)	Coordinatio n Issue	Barely Clipping	9/5/2012	9/7/2012	2	E	CON	2	2	Bend Lower
16	717	1	E M	CON- D'MPSA	H- H(X)	Coordinatio n Issue	Barely Clipping	9/5/2012	9/7/2012	2	M	D'MPSA	2	2	Reshap e
16	718	1	E M	CON- D'LPSA	H- H(X)	Coordinatio n Issue	Barely Clipping	9/5/2012	9/7/2012	2	M	D'LPSA	2	2	Reshap e
16	718	1	F M	MAIN- D'LPSA	H- H(X)	Coordinatio n Issue	Hard	9/5/2012	9/7/2012	2	M	D'LPSA	2	2	Reshap e
16	719	1	M P	VAV-SAN	H- H(X)	Coordinatio n Issue	Clearanc e	9/5/2012	9/7/2012	2	M,P	VAV,SAN	2	1	Reshap e_Raise
16	720	1	M P	VAV,D'LPS A-SAN	H- H(X)	Coordinatio n Issue	Hard	9/5/2012	9/7/2012	2	P	SAN	2	3	Raise
16	721	1	M P	D'LPSA- DCW	H-V	Coordinatio n Issue	Hard	9/5/2012	9/7/2012	2	P	DCW	2	2	Reroute
16	722	1	M P	R'LPSA- DHW	H- H(X)	Coordinatio n Issue	Hard	9/5/2012	9/26/2012	21	M,P	R'LPSA,D HW	2	3	Reroute _Raise
16	723	1	F M	MAIN- D'LPSA	H- H(X)	Coordinatio n Issue	Hard	9/5/2012	9/7/2012	2	F	MAIN	2	2	Reroute
16	724	1	F M	BRANCH- D'MPSA	H-H	Coordinatio n Issue	Barely Clipping	9/5/2012	9/7/2012	2	F	BRANCH	2	2	Move
16	725	1	F	MAIN-	H-H	Coordinatio	Hard	9/5/2012	9/26/2012	21	F,M	MAIN,D'	2	4	Reroute

			M	D'MPSA		n Issue						MPSA			,Lower
16	726	1	FM	MAIN-D'MPSA	H-H	Coordination Issue	Barely Clipping	9/5/2012	9/7/2012	2	F	MAIN	2	3	Raise
16	727	1	FM	BRANCH-D'MPSA	V-H	Coordination Issue	Hard	9/5/2012	9/7/2012	2	F	BRANCH	2	2	Move
16	729	1	FM	BRANCH-D'MPSA	H-H(X)	Coordination Issue	Hard	9/5/2012	9/7/2012	2	F	BRANCH	2	2	Lower
16	730	1	FM	BRANCH-VAV	H-V	Coordination Issue	Clearance	9/5/2012	9/7/2012	2	F	BRANCH	2	1	Reroute
16	731	1	AF	CLG-MAIN	H-H	Modeling Error	Barely Clipping	9/5/2012	9/26/2012	21	F	MAIN	2	2	Raise
16	732	1	EF	LGT-BRANCH	V-H	Modeling Error	Hard	9/5/2012	11/12/2012	68	N/A	N/A	2	2	Ignore
16	733	1	AF	FURN-HEAD	H-V	Modeling Error	Hard	9/5/2012	9/26/2012	21	F	HEAD	2	2	Move
16	734	1	AF	CLG-BRANCH	H-H	Modeling Error	Clearance	9/5/2012	9/26/2012	21	F	BRANCH	2	1	Raise
16	735	1	AF	FURN-BRANCH	H-H	Coordination Issue	Soft	9/5/2012	9/7/2012	2	F	BRANCH	2	1	Move
17	802	1	FP	MAIN-SAN	H-H	Coordination Issue	Hard	9/7/2012	9/26/2012	19	P	SAN	2	2	Move
17	803	1	FP	MAIN-DCW	H-H(X)	Coordination Issue	Barely Clipping	9/7/2012	9/26/2012	19	P	DCW	2	2	Raise
17	805	1	EM	LGT-GRL	H-H	Coordination Issue	Hard	9/7/2012	9/26/2012	19	M	GRL	2	2	Move
17	806	1	EP	CON-DCW	H-V	Coordination Issue	Barely Clipping	9/7/2012	9/26/2012	19	N/A	N/A	2	2	FA
17	807	1	EM	LGT-VAV	H-V	Coordination Issue	Clearance	9/7/2012	9/26/2012	19	M	VAV	2	1	Verify
17	808	1	MP	D'LPEA-DHW	H-H	Coordination Issue	Hard	9/7/2012	9/26/2012	19	M	D'LPEA	2	3	Reshape
17	810	1	FM	MAIN-VAV	H-V	Coordination Issue	Clearance	9/7/2012	9/26/2012	19	F	MAIN	2	1	Reroute
17	812	1	F	BRANCH-	V-H	Coordinatio	Clearanc	9/7/2012	9/26/2012	19	F	BRANCH	2	1	Reroute

			M	VAV		n Issue	e								
17	813	1	F M	BRANCH-R'LPSA	H-H	Coordination Issue	Hard	9/7/2012	9/26/2012	19	F	BRANCH	2	2	Reroute
17	814	1	F M	MAIN-D'MPSA	H-H	Coordination Issue	Clearance	9/7/2012	9/26/2012	19	N/A	N/A	2	1	FA
17	815	1	EP	JBOX-DCW	V-H	Coordination Issue	Clearance	9/7/2012	9/26/2012	19	N/A	N/A	2	1	Ignore
18	901	2	ES	CON-STLB	H-H(X)	Modeling Error	Clearance	9/26/2012	9/26/2012	0	N/A	N/A	2	1	FA
18	902	2	PS	STM-STLB	H-H(X)	Modeling Error	Hard	9/26/2012	10/5/2012	9	P	STM	2	2	Lower
18	903	2	PS	SAN-STLB	V-H	Modeling Error	Hard	9/26/2012	10/5/2012	9	P	SAN	2	2	Lower
18	904	2	M S	VAV-STLB	V-H	Modeling Error	Hard	9/26/2012	10/5/2012	9	M	VAV	2	2	Move
18	905	2	M S	VAV-STLB	V-H	Modeling Error	Hard	9/26/2012	11/12/2012	47	M	VAV	2	3	Lower
18	906	2	M S	R'LPSA-STLB	H-H(X)	Modeling Error	Hard	9/26/2012	11/12/2012	47	M	R'LPSA	2	2	Lower
18	907	2	M S	R'MPSA-STLB	H-H(X)	Modeling Error	Barely Clipping	9/26/2012	11/12/2012	47	M	R'MPSA	2	2	Lower
18	908	2	M S	D'LPSA-STLB	H-H(X)	Modeling Error	Barely Clipping	9/26/2012	11/12/2012	47	M	D'LPSA	2	2	Lower
20	1001	3	AE	FURN-LGT	V-H	Design Issue	Soft	10/15/2012	11/12/2012	28	A	FURN	2	6	Move
20	1002	3	A M	FURN-VAV	S-H	Design Issue	Soft	10/15/2012	11/12/2012	28	M	VAV	2	1	Remove_Reroute
20	1003	3	AE	FURN-LGT	V-H	Design Issue	Soft	10/15/2012	11/12/2012	28	E	LGT	2	4	Move
20	1004	3	E M	LGT-GRL	H-H	Coordination Issue	Hard	10/15/2012	11/12/2012	28	M	GRL	2	2	Move
20	1005	3	M S	VAV-STLB	V-H	Modeling Error	Hard	10/15/2012	11/12/2012	28	M	VAV	2	2	Reshape_Move

20	1006	3	MS	D'MPSA-STLB	H-H(X)	Modeling Error	Barely Clipping	10/15/2012	11/12/2012	28	M	D'MPSA	2	2	Reshape
20	1007	3	MS	VAV-STLB	V-H	Modeling Error	Hard	10/15/2012	11/12/2012	28	M	VAV	2	2	Lower
20	1008	3	MS	R'MPSA-STLB	H-H(X)	Modeling Error	Barely Clipping	10/15/2012	11/12/2012	28	M	R'MPSA	2	2	Lower
20	1009	3	MS	D'MPSA-STLB	H-H(X)	Modeling Error	Barely Clipping	10/15/2012	11/12/2012	28	M	D'MPSA	2	2	Move
20	1010	3	MS	D'LPRA-STLB	H-H(X)	Modeling Error	Hard	10/15/2012	11/12/2012	28	M	D'LPRA	2	2	Move
20	1011	3	MS	R'LPSA-STLB	H-H(X)	Modeling Error	Barely Clipping	10/15/2012	11/12/2012	28	M	R'LPSA	2	2	Lower
20	1015	3	PS	DHW-STLB	V-H	Modeling Error	Hard	10/15/2012	11/12/2012	28	P	DHW	2	2	Move
20	1016	3	PS	NGAS-STLCOL	V-V	Modeling Error	Clearance	10/15/2012	11/12/2012	28	P	NGAS	2	1	Move
20	1017	3	ES	CON-STLB	H-H(X)	Modeling Error	Clearance	10/15/2012	11/12/2012	28	E	CON	2	8	Lower
20	1018	3	FS	MAIN-STLB	V-H	Modeling Error	Hard	10/15/2012	11/12/2012	28	F	MAIN	2	2	Move
20	1019	3	AM	CLG-D'MPSA	H-H	Modeling Error	Hard	10/15/2012	11/12/2012	28	M	D'MPSA	2	2	Reshape
22	1101	1	MP	R'LPEA-CHWS	H-H(X)	Coordination Issue	Barely Clipping	10/29/2012	11/12/2012	14	N/A	N/A	2	2	FA
22	1102	1	MP	R'LPSA-SAN	V-H	Coordination Issue	Barely Clipping	10/29/2012	11/12/2012	14	M	R'LPSA	2	2	Move
22	1103	1	MP	D'LPRA-DCW	H-H	Coordination Issue	Hard	10/29/2012	11/12/2012	14	P	DCW	2	2	Raise
22	1104	1	MP	R'LPEA-DHWR	H-H(X)	Coordination Issue	Barely Clipping	10/29/2012	11/12/2012	14	M	R'LPEA	2	2	Reroute
22	1105	1	MP	D'MPSA-DCW	H-H	Coordination Issue	Barely Clipping	10/29/2012	11/12/2012	14	P	DCW	2	2	Raise
22	1106	1	MP	D'MPSA-DHW	H-H	Coordination Issue	Barely Clipping	10/29/2012	11/12/2012	14	P	DHW	2	2	Raise

22	110 7	1	E M	CON-D'LPSA	H-H(X)	Coordinatio n Issue	Hard	10/29/2012	11/12/2012	14	N/A	N/A	2	2	FA
22	110 8	1	E M	HNGR-D'MPSA	H-H	Coordinatio n Issue	Barely Clipping	10/29/2012	11/12/2012	14	N/A	N/A	2	2	FA
22	110 9	1	F M	BRANCH-R'LPSA	H-H	Coordinatio n Issue	Barely Clipping	10/29/2012	11/12/2012	14	M	R'LPSA	2	2	Raise
22	111 0	1	M P	MAIN-CHWS	H-H(X)	Coordinatio n Issue	Barely Clipping	10/29/2012	11/12/2012	14	N/A	N/A	2	2	FA
22	111 1	1	M S	R'LPSA-STLB	H-H(X)	Modeling Error	Barely Clipping	10/29/2012	11/12/2012	14	M	R'LPSA	2	2	Move
22	111 2	1	M S	R'LPEA-STLCONN	H-V	Modeling Error	Barely Clipping	10/29/2012	11/12/2012	14	M	R'LPEA	2	2	Lower
22	111 3	1	M S	FLEX'LPSA-KIC	V-V	Modeling Error	Hard	10/29/2012	11/12/2012	14	M	FLEX'LPS A	2	2	Reroute
22	111 4	1	A M	FRM-R'MPSA	V-H	Modeling Error	Hard	10/29/2012	11/12/2012	14	M	R'MPSA	2	2	Move
22	111 5	1	EP	CON-DHW	H-H(X)	Coordinatio n Issue	Barely Clipping	10/29/2012	11/12/2012	14	P	DHW	2	3	Raise
22	111 6	1	EP	CON-DHWR	H-H(X)	Coordinatio n Issue	Barely Clipping	10/29/2012	11/12/2012	14	N/A	N/A	2	6	FA
22	111 7	1	EP	CON-DCW	H-H(X)	Coordinatio n Issue	Barely Clipping	10/29/2012	11/12/2012	14	N/A	N/A	2	6	FA
22	111 8	1	FP	MAIN-DCW	H-H(X)	Coordinatio n Issue	Barely Clipping	10/29/2012	11/12/2012	14	F	MAIN	2	2	Move
22	111 9	1	AP	FRM-DCW	V-H	Modeling Error	Hard	10/29/2012	11/12/2012	14	N/A	N/A	2	2	FA
22	112 0	1	PS	DCW,DHW -STLB	H-H(X)	Modeling Error	Barely Clipping	10/29/2012	11/12/2012	14	N/A	N/A	2	3	FA
22	112 1	1	EF	JBOX-BRANCH	V-H	Coordinatio n Issue	Hard	10/29/2012	11/12/2012	14	N/A	N/A	2	2	FA
22	112 2	1	ES	CON-KIC	H-W	Coordinatio n Issue	Barely Clipping	10/29/2012	11/20/2012	22	E	CON	2	2	Move
22	112 3	1	AF	FRM-MAIN	V-H	Design Issue	Hard	10/29/2012	11/20/2012	22	A	FRM	2	2	Verify

24	1201	2	MS	D'LPRA-STLB	V-H	Modeling Error	Barely Clipping	10/29/2012	11/12/2012	14	M	D'LPRA	2	2	Lower
24	1202	2	MS	R'LPSA-STLB	V-H	Modeling Error	Hard	10/29/2012	11/12/2012	14	M	R'LPSA	2	2	Move
24	1203	2	A	FRM	V	Modeling Error	Soft	10/29/2012	11/12/2012	14	A	FRM	1	2	Verify
24	1204	2	AM	FRM,CLG-VAV	V,H-V	Modeling Error	Clearance	10/29/2012	11/12/2012	14	M	VAV	2	2	Remove
24	1204	2	AM	FRM-D'LPSA	V-H	Modeling Error	Barely Clipping	10/29/2012	11/12/2012	14	M	D'LPSA	2	2	Reroute
24	1205	2	MP	R'LPEA-SAN	H-H(X)	Coordination Issue	Hard	10/29/2012	11/12/2012	14	P	SAN	2	2	Lower
24	1206	2	MP	R'LPSA-STM	H-H	Coordination Issue	Hard	10/29/2012	11/12/2012	14	M	R'LPSA	2	2	Reroute
24	1207	2	EM	CON-D'LPSA	V-H	Coordination Issue	Barely Clipping	10/29/2012	11/12/2012	14	N/A	N/A	2	2	FA
24	1210	2	EM	CON-VAV	H-H	Coordination Issue	Barely Clipping	10/29/2012	11/12/2012	14	M	VAV	2	7	Remove
24	1210	2	AE	FRM-CON	V-H	Coordination Issue	Hard	10/29/2012	11/12/2012	14	N/A	N/A	2	7	Ignore
24	1212	2	EM	CON-FLEX'MPSA,R'LPSA	H-H(X)	Coordination Issue	Barely Clipping	10/29/2012	11/12/2012	14	N/A	N/A	2	3	FA
24	1213	2	EM	CON-R'LPSA	H-V	Coordination Issue	Hard	10/29/2012	11/12/2012	14	M	R'LPSA	2	4	Reroute
24	1218	2	FM	HEAD-GRL	V-V	Coordination Issue	Hard	10/29/2012	11/12/2012	14	M	GRL	2	4	Move
24	1219	2	FM	MAIN-D'LPSA	H-V	Coordination Issue	Barely Clipping	10/29/2012	11/12/2012	14	M	D'LPSA	2	3	Raise
24	1220	2	FM	MAIN-VAV	H-V	Coordination Issue	Clearance	10/29/2012	11/12/2012	14	N/A	N/A	2	1	Ignore
24	1221	2	FM	BRANCH-R'LPSA	V-H	Coordination Issue	Barely Clipping	10/29/2012	11/12/2012	14	M	R'LPSA	2	2	Reroute
24	122	2	F	HEAD-GRL	V-V	Coordinatio	Hard	10/29/2012	11/12/2012	14	M	GRL	2	4	Move

	2		M			n Issue								
24	1223	2	FM	BRANCH-R'LPSA	H-H(X)	Coordination Issue	Barely Clipping	10/29/2012	11/12/2012	14	M	R'LPSA	2	3	Raise
24	1224	2	MP	CHWR,CHWS-SAN'SLV	V-V	Modeling Error	Barely Clipping	10/29/2012	11/20/2012	22	P	SAN'SLV	2	4	Remove
24	1225	2	EP	CON-DHWR	H-H(X)	Coordination Issue	Clearance	10/29/2012	11/12/2012	14	P	DHWR	2	1	Lower
24	1226	2	EF	CON-BRANCH	H-H(X)	Coordination Issue	Barely Clipping	10/29/2012	11/12/2012	14	N/A	N/A	2	3	FA
24	1301	1	AE	FURN-LGT	V-V	Coordination Issue	Soft	11/5/2012	11/20/2012	15	E	LGT	2	1	Move
24	1302	1	AE	FURN-LGT	V-V	Coordination Issue	Soft	11/5/2012	11/20/2012	15	E	LGT	2	1	Move
24	1305	1	AM	FURN-VAV	V-V	Coordination Issue	Soft	11/5/2012	12/6/2012	31	M	VAV	2	1	Move
26	1407	2	FM	BRANCH-VAV	H-V	Coordination Issue	Clearance	11/5/2012	11/12/2012	7	N/A	N/A	2	1	Ignore
26	1408	2	MS	R'LPSA-STLB	H-H(X)	Coordination Issue	Barely Clipping	11/5/2012	11/20/2012	15	M	R'LPSA	2	2	Lower
26	1408	2	EM	CON-R'LPSA	H-H(X)	Coordination Issue	Barely Clipping	11/5/2012	11/20/2012	15	M	R'LPSA	2	2	Lower
26	1409	2	FP	MAIN-CHWR	V-H	Coordination Issue	Hard	11/5/2012	11/20/2012	15	F	MAIN	2	2	Move
26	1501	3	MS	D'LPSA-STLB	H-H(X)	Modeling Error	Clearance	11/5/2012	11/20/2012	15	N/A	N/A	2	1	FA
26	1502	3	PS	DHW-KIC	H-V	Modeling Error	Barely Clipping	11/5/2012	12/4/2012	29	P	DHW	3	4	Move
26	1502	3	MS	D'LPEA-KIC	H-V	Modeling Error	Hard	11/5/2012	11/20/2012	15	M	D'LPEA	3	4	Raise,Move
26	1503	3	MP	R'LPSA-DCW	H-H(X)	Coordination Issue	Clearance	11/5/2012	11/20/2012	15	M	R'LPSA	2	2	Reroute
26	1504	3	EM	CON-D'MPSA	H-H	Coordination Issue	Clearance	11/5/2012	11/20/2012	15	N/A	N/A	2	1	FA

26	1505	3	EM	CON-R'LPSA	V-H	Coordination Issue	Clearance	11/5/2012	11/20/2012	15	N/A	N/A	2	1	FA
26	1506	3	EM	CON-D'LPSA	H-H(X)	Coordination Issue	Hard	11/5/2012	12/4/2012	29	E	CON	2	7	Raise
26	1507	3	EM	CON-R'MPSA	H-H(X)	Coordination Issue	Barely Clipping	11/5/2012	12/4/2012	29	E	CON	2	5	Raise
26	1508	3	EM	CON-D'LPSA,D'MPSA	H-H(X)	Coordination Issue	Hard	11/5/2012	12/4/2012	29	E	CON	2	4	Move
26	1510	3	FM	BRANCH-VAV	H-H	Coordination Issue	Clearance	11/5/2012	12/6/2012	31	F	BRANCH	2	1	Move
26	1512	3	EF	LGT-HEAD	H-V	Coordination Issue	Hard	11/5/2012	11/20/2012	15	E	LGT	2	4	Move
26	1513	3	FS	BRANCH-KIC	H-V	Coordination Issue	Hard	11/5/2012	12/6/2012	31	F	BRANCH	2	2	Reroute
26	1601	1	MP	D'LPSA-DCW	H-H	Coordination Issue	Clearance	11/7/2012	11/12/2012	5	N/A	N/A	2	2	FA
26	1602	1	EP	CON-DCW	H-H(X)	Coordination Issue	Barely Clipping	11/7/2012	11/12/2012	5	N/A	N/A	2	6	FA
26	1605	1	FS	DCW-STLB	H-H(X)	Modeling Error	Hard	11/7/2012	11/12/2012	5	N/A	N/A	2	2	FA
26	1608	3	FM	BRANCH-D'LPSA	V-H	Coordination Issue	Hard	11/7/2012	12/6/2012	29	M	D'LPSA	2	2	Move
26	1610	3	EF	BRANCH,MAIN-JBOX	H-V	Coordination Issue	Hard	11/7/2012	11/20/2012	13	N/A	N/A	2	3	FA
27	1706	3	AE	FURN-LGT	V-V	Design Issue	Soft	11/10/2012	11/20/2012	10	E	LGT	2	1	Move
27	1708	3	MP	D'LPEA-DHW	H-H	Coordination Issue	Barely Clipping	11/10/2012	11/20/2012	10	M	D'LPEA	2	2	Move
27	1710	3	FM	BRANCH-D'LPSA	H-H	Coordination Issue	Barely Clipping	11/10/2012	11/20/2012	10	F	BRANCH	2	2	Move
27	1714	3	EM	CON-R'MPSA	H-H(X)	Coordination Issue	Barely Clipping	11/10/2012	11/29/2012	19	E	CON	2	6	Raise
27	171	3	E	CON-	V-H	Coordinatio	Barely	11/10/2012	11/29/2012	19	M	R'LPSA	2	2	Move

	5		M	R'LPSA		n Issue	Clipping								
27	1716	3	FP	MAIN-CHW	V-H	Coordination Issue	Hard	11/10/2012	11/20/2012	10	F	MAIN	2	2	Move
28	1801	4	MS	R'MPSA-STLB	H-H(X)	Modeling Error	Barely Clipping	11/14/2012	11/27/2012	13	M	R'MPSA	2	2	Lower
28	1802	4	PS	DHW-STLB	V-H	Modeling Error	Barely Clipping	11/14/2012	11/27/2012	13	N/A	N/A	2	2	FA
28	1803	4	EM	LGT-GRL	H-H	Coordination Issue	Hard	11/14/2012	11/27/2012	13	M	GRL	2	3	Move
28	1804	4	EM	LGT-GRL	H-H	Coordination Issue	Hard	11/14/2012	11/27/2012	13	M	GRL	2	3	Move
28	1805	4	EM	LGT-D'MPSA	H-H	Coordination Issue	Hard	11/14/2012	11/27/2012	13	E	LGT	2	2	Move
28	1806	4	EM	LGT-R'LPSA	H-H	Coordination Issue	Hard	11/14/2012	11/27/2012	13	M	R'LPSA	2	3	Raise
28	1807	4	EM	LGT-GRL	H-H	Coordination Issue	Hard	11/14/2012	11/27/2012	13	M	GRL	2	3	Move
28	1808	4	MM	R'MPSA-R'LPSA	H-H(X)	Coordination Issue	Barely Clipping	11/14/2012	11/27/2012	13	M	R'LPSA	2	4	Reroute
28	1809	4	EM	LGT-GRL	H-H	Coordination Issue	Hard	11/14/2012	11/27/2012	13	M	GRL	2	3	Move
28	1810	4	EM	LGT-FCU	H-H	Coordination Issue	Hard	11/14/2012	11/27/2012	13	E	LGT	2	2	Move
28	1811	4	EF	LGT-HEAD	H-V	Coordination Issue	Hard	11/14/2012	11/27/2012	13	F	HEAD	2	2	Move
28	1812	4	EF	LGT-HEAD	H-V	Coordination Issue	Hard	11/14/2012	11/27/2012	13	F	HEAD	2	2	Move
28	1812	4	EF	LGT-HEAD	H-V	Coordination Issue	Hard	11/14/2012	11/27/2012	13	F	HEAD	2	2	Move
28	1812	4	EF	LGT-HEAD	H-V	Coordination Issue	Hard	11/14/2012	11/27/2012	13	F	HEAD	2	2	Move
28	1812	4	EF	LGT-HEAD	H-V	Coordination Issue	Hard	11/14/2012	11/27/2012	13	F	HEAD	2	2	Move
28	181	4	EF	LGT-HEAD	H-V	Coordinatio	Hard	11/14/2012	11/27/2012	13	F	HEAD	2	2	Move

	2					n Issue									
28	181 2	4	EF	LGT-HEAD	H-V	Coordinatio n Issue	Hard	11/14/2012	11/27/2012	13	F	HEAD	2	2	Move
28	181 2	4	EF	LGT-HEAD	H-V	Coordinatio n Issue	Hard	11/14/2012	11/27/2012	13	F	HEAD	2	2	Move
28	181 2	4	EF	LGT-HEAD	H-V	Coordinatio n Issue	Hard	11/14/2012	11/27/2012	13	F	HEAD	2	2	Move
28	181 2	4	EF	LGT-HEAD	H-V	Coordinatio n Issue	Hard	11/14/2012	11/27/2012	13	F	HEAD	2	2	Move
28	181 3	4	M P	D'MPSA- DHWR	H-V	Coordinatio n Issue	Barely Clipping	11/14/2012	11/27/2012	13	N/A	N/A	2	2	FA
28	181 4	4	F M	MAIN-FCU	H-V	Coordinatio n Issue	Clearanc e	11/14/2012	11/27/2012	13	F	MAIN	2	1	Reroute
28	181 5	4	E M	CON- D'LPSA,D' MPSA	H- H,H(X)	Coordinatio n Issue	Hard	11/14/2012	11/29/2012	15	E	CON	2	4	Raise
28	181 6	4	E M	CON- R'LPSA,D'L PSA	H- H,H(X)	Coordinatio n Issue	Hard	11/14/2012	11/29/2012	15	E	CON	2	7	Move
28	181 7	4	E M	CON- D'LPSA	H- H(X)	Coordinatio n Issue	Hard	11/14/2012	11/29/2012	15	E	CON	2	7	Raise
28	181 8	4	E M	CON- D'MPSA	H-H	Coordinatio n Issue	Clearanc e	11/14/2012	11/29/2012	15	E	CON	2	1	Move
28	181 9	4	E M	CON- R'LPSA	H-V	Coordinatio n Issue	Hard	11/14/2012	11/27/2012	13	M	R'LPSA	2	3	Reroute
28	182 0	4	E M	CON- R'LPSA	H-V	Coordinatio n Issue	Hard	11/14/2012	11/27/2012	13	M	R'LPSA	2	6	Reroute
28	182 2	4	FP	BRANCH- SAN	H-V	Coordinatio n Issue	Barely Clipping	11/14/2012	11/27/2012	13	F	BRANCH	2	2	Remove
29	190 1	4	AF	FURN- HEAD	V-V	Modeling Error	Hard	11/26/2012	11/29/2012	3	F	HEAD	2	2	Remove
29	190 2	4	EP	CON- DHWR	H- H(X)	Coordinatio n Issue	Hard	11/26/2012	11/29/2012	3	E	CON	2	7	Raise
29	190	4	E	LGT-GRL	H-H	Coordinatio	Hard	11/26/2012	12/4/2012	8	M	GRL	2	3	Move

	4		M			n Issue									
29	190 5	4	E M	LGT-GRL	H-H	Coordinatio n Issue	Hard	11/26/2012	12/4/2012	8	M	GRL	2	3	Move
29	190 7	4	E M	LGT-GRL	H-H	Coordinatio n Issue	Hard	11/26/2012	12/4/2012	8	M	GRL	2	3	Move
29	190 8	4	F M	HEAD-GRL	H-V	Coordinatio n Issue	Hard	11/26/2012	11/29/2012	3	F	HEAD	2	3	Move
29	190 9	4	E M	HNGR-R'LPSA	V-H	Coordinatio n Issue	Hard	11/26/2012	11/29/2012	3	E	CON	2	2	Move
30	200 1	5	M S	R'LPSA-STL	H-H(X)	Coordinatio n Issue	Barely Clipping	11/26/2012	11/30/2012	4	M	R'LPSA	2	2	Reroute
30	200 1	5	M P	R'LPSA-STM	H-H(X)	Coordinatio n Issue	Barely Clipping	11/26/2012	11/30/2012	4	M	R'LPSA	2	2	Reroute
30	200 2	5	M S	D'LPSA-STL	H-H	Coordinatio n Issue	Hard	11/26/2012	11/30/2012	4	M	D'LPSA	2	5	Lower
30	200 3	5	M S	D'LPSA-STL	H-H(X)	Coordinatio n Issue	Hard	11/26/2012	11/30/2012	4	M	D'LPSA	2	2	Reshap e_Raise
30	200 3	5	M P	D'LPSA-STM	H-H(X)	Coordinatio n Issue	Hard	11/26/2012	11/30/2012	4	M	D'LPSA	2	2	Reshap e_Raise
30	200 4	5	M S	D'LPEA-STL	H-H	Coordinatio n Issue	Hard	11/26/2012	11/30/2012	4	M	D'LPEA	2	3	Reshap e
30	200 5	5	M S	D'LPSA-STL	H-H(X)	Coordinatio n Issue	Hard	11/26/2012	11/30/2012	4	M	D'LPSA	2	2	Lower
30	200 6	5	M S	D'LPSA-STL	H-H(X)	Coordinatio n Issue	Barely Clipping	11/26/2012	11/30/2012	4	M	D'LPSA	2	2	Lower
30	200 6	5	M S	R'LPSA-STLB	H-V	Coordinatio n Issue	Hard	11/26/2012	12/4/2012	8	M	R'LPSA	2	2	Reroute
30	200 7	5	M S	D'LPSA-STL	H-H(X)	Coordinatio n Issue	Barely Clipping	11/26/2012	11/30/2012	4	M	D'LPSA	2	2	Lower
30	200 8	5	M S	R'LPSA-STLB	H-V	Coordinatio n Issue	Hard	11/26/2012	11/30/2012	4	M	R'LPSA	2	2	Lower
30	200 9	5	M S	R'LPSA-KIC	H-V	Coordinatio n Issue	Hard	11/26/2012	11/30/2012	4	M	R'LPSA	2	4	Move
30	201	5	M	D'LPRA-KIC	V-V	Coordinatio	Hard	11/26/2012	11/30/2012	4	M	D'LPRA	2	2	Move

	0		S			n Issue									
30	201 1	5	M S	D'LPOA-STLB	H-H(X)	Coordinatio n Issue	Clearanc e	11/26/2012	11/30/2012	4	M	D'LPOA	2	1	Lower
30	201 2	5	M M	D'MPSA-CHWR	H-H(X)	Coordinatio n Issue	Hard	11/26/2012	11/30/2012	4	M	CHWR	2	4	Reroute
30	201 3	5	M P	D'LPSA-STM	H-H(X)	Coordinatio n Issue	Barely Clipping	11/26/2012	11/30/2012	4	P	STM	2	2	Move
30	201 4	5	M P	D'LPSA-STM	H-H(X)	Coordinatio n Issue	Hard	11/26/2012	11/30/2012	4	M	D'LPSA	2	2	Reroute
30	201 5	5	M P	D'LPSA-STM	H-H(X)	Coordinatio n Issue	Hard	11/26/2012	11/30/2012	4	M	D'LPSA	2	2	Reroute
31	210 3	3	F M	HEAD-GRL	V-V	Coordinatio n Issue	Hard	11/29/2012	12/6/2012	7	F	HEAD	2	3	Move
31	210 5	3	E M	LGT-R'LPSA	H-H	Coordinatio n Issue	Hard	11/29/2012	11/30/2012	1	M	R'LPSA	2	2	Reroute
31	210 6	3	E M	LGT-D'MPSA	H-H	Coordinatio n Issue	Hard	11/29/2012	12/6/2012	7	E	LGT	2	4	Move
31	210 6	3	E M	LGT-GRL	H-H	Coordinatio n Issue	Hard	11/29/2012	11/30/2012	1	M	GRL	2	10	Move
31	210 7	3	EF	LGT-BRANCH	H-H	Coordinatio n Issue	Barely Clipping	11/29/2012	12/6/2012	7	F	BRANCH	2	4	Move
31	210 8	3	EF	LGT-MAIN	H-H	Coordinatio n Issue	Barely Clipping	11/29/2012	12/6/2012	7	F	MAIN	2	2	Reroute
31	210 9	3	EF	LGT-BRANCH	V-H	Coordinatio n Issue	Clearanc e	11/29/2012	12/6/2012	7	F	BRANCH	2	1	Move
31	211 0	3	F M	BRANCH-R'LPSA	H-H(X)	Coordinatio n Issue	Hard	11/29/2012	11/30/2012	1	M	R'LPSA	2	2	Raise
31	211 3	3	E M	HNGR-R'LPSA	V-H	Coordinatio n Issue	Barely Clipping	11/29/2012	12/6/2012	7	M	R'LPSA	2	2	Move
31	211 4	3	FP	BRANCH-SAN	H-H(X)	Coordinatio n Issue	Hard	11/29/2012	12/6/2012	7	F	BRANCH	2	2	Move
31	211 5	3	AP	WALL-PLUMB	V-V	Modeling Error	Hard	11/29/2012	12/4/2012	5	P	PLUMB	2	5	Move
32	220	5	M	R'LPSA-KIC	H-	Coordinatio	Hard	11/30/2012	12/4/2012	4	M	R'LPSA	2	2	Lower

	1		S		H(X)	n Issue									
32	2202	5	MS	R'LPEA-STL	H-H(X)	Coordination Issue	Hard	11/30/2012	12/4/2012	4	M	R'LPSA,R'LPEA	2	3	Raise,Reroute
32	2202	5	AM	WALL-VAV	V-H	Coordination Issue	Clearance	11/30/2012	12/4/2012	4	M	VAV	2	1	Verify
32	2203	5	MS	R'LPSA-STL	V-H	Modeling Error	Hard	11/30/2012	12/4/2012	4	M	R'LPSA	2	2	Move
32	2205	5	FS	MAIN-KIC	H-V	Modeling Error	Barely Clipping	11/30/2012	12/4/2012	4	F	MAIN	2	2	Move
32	2206	5	ES	CON-KIC	H-V	Modeling Error	Hard	11/30/2012	12/4/2012	4	E	CON	2	6	Reroute
32	2207	5	AM	CLG-D'LPRA	H-H	Modeling Error	Hard	11/30/2012	12/4/2012	4	M	D'LPRA	2	2	Raise
32	2208	5	AP	CLG-SAN	H-H	Modeling Error	Hard	11/30/2012	12/4/2012	4	P	SAN	2	2	Remove
32	2210	5	EM	CON-D'LPSA	H-H(X)	Coordination Issue	Hard	11/30/2012	12/4/2012	4	E	CON	2	2	Raise
32	2211	5	EM	CON-D'MPSA	H-H(X)	Coordination Issue	Hard	11/30/2012	12/4/2012	4	E	CON	2	7	Raise
32	2212	5	EM	CON-D'LPOA	H-H(X)	Coordination Issue	Hard	11/30/2012	12/4/2012	4	E	CON	2	7	Raise
32	2212	5	FM	HEAD-D'LPOA	V-H	Coordination Issue	Hard	11/30/2012	12/4/2012	4	F	HEAD	2	4	Move
32	2214	5	EM	CON-D'LPSA	H-H	Coordination Issue	Hard	11/30/2012	12/4/2012	4	E	CON	2	2	Move
32	2215	5	EM	HNGR-D'LPSA	H-H	Coordination Issue	Barely Clipping	11/30/2012	12/4/2012	4	E	HNGR	2	2	Move
32	2216	5	EM	CON-R'LPSA	H-H	Coordination Issue	Barely Clipping	11/30/2012	12/4/2012	4	E	CON	2	4	Raise
32	2217	5	EM	CON-FCU	H-H	Coordination Issue	Hard	11/30/2012	12/4/2012	4	E	CON	2	7	Raise
32	2218	5	EM	CON-D'LPSA	H-H(X)	Coordination Issue	Hard	11/30/2012	12/4/2012	4	E	CON	2	5	Raise
32	221	5	M	CHWR-SAN	V-H	Coordinatio	Hard	11/30/2012	12/4/2012	4	P	SAN	2	2	Move

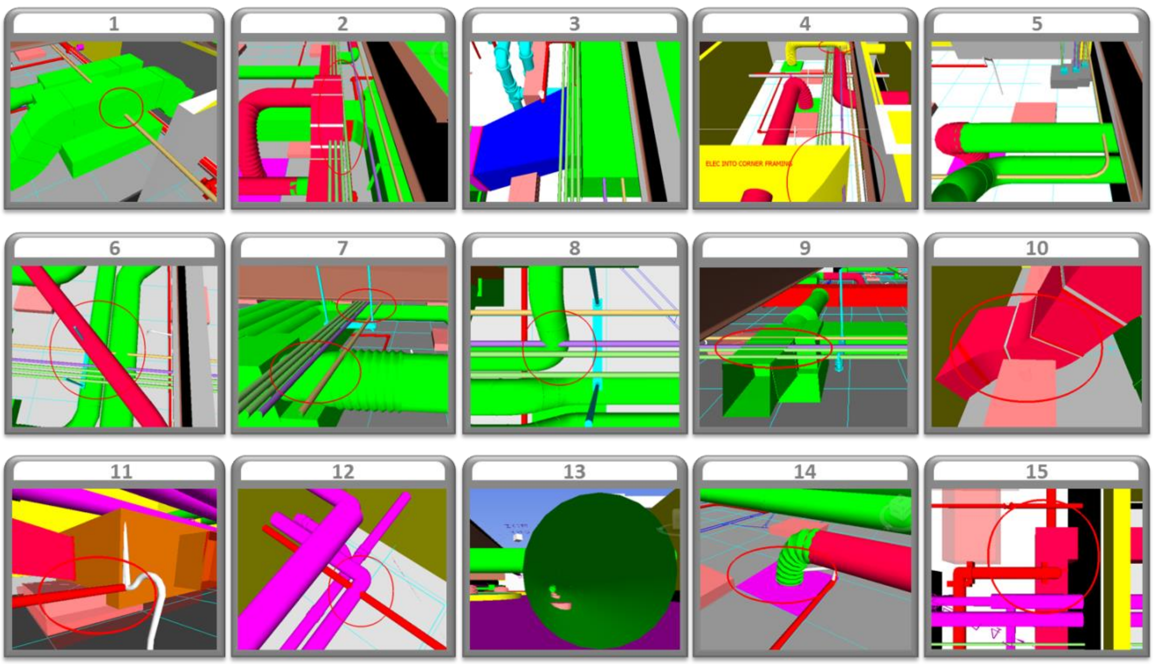
	9		P			n Issue									
32	2220	5	EM	CON-CHWR	H-V	Coordination Issue	Hard	11/30/2012	12/4/2012	4	E	CON	2	5	Raise
33	2303	3	EM	CON-R'LPSA	H-H(X)	Coordination Issue	Barely Clipping	12/3/2012	12/6/2012	3	M	R'LPSA	2	6	Raise
33	2304	3	ES	CON-STLB	H-H(X)	Modeling Error	Hard	12/3/2012	12/6/2012	3	E	CON	2	9	Lower
34	2401	3	FM	BRANCH-D'LPSA	H-H(X)	Coordination Issue	Barely Clipping	12/4/2012	12/6/2012	2	M	D'LPSA	2	2	Reroute
34	2402	3	EM	HNGR-R'LPSA	V-H	Coordination Issue	Hard	12/4/2012	12/6/2012	2	M	R'LPSA	2	2	Reroute
34	2404	3	EM	CON-R'LPSA	H-H(X)	Coordination Issue	Barely Clipping	12/4/2012	12/6/2012	2	M	R'LPSA	2	6	Raise

Appendix D – Novice Experiment Design

D.1 Procedures

1. Click on the link that was sent to you by email (**https://meeting.austin.utexas.edu/XXX/**)
2. Enter as a Guest
3. Download and open the files (.nwd & .doc) from "File Share"
4. Once ready, start sharing desktop
5. Analyze the clashes in the model and fill in the "Clash Report Template" with your analysis
6. When you have finished, stop sharing desktop
7. Save the clash report document and send it back to Li (celeste.wl05@gmail.com)

D.2 Scenarios



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