Integrating BIM and Safety: An Automated Rule-Based Checking System for Safety Planning and Simulation

Sijie Zhang
School of Civil and Environmental Engineering, Georgia Institute of Technology, U.S.A.
E-Mail: annazhang@gatech.edu

Jin-Kook Lee
College of Architect, Georgia Institute of Technology, U.S.A.
E-Mail: jklee@gatech.edu

Manu Venugopal
School of Civil and Environmental Engineering, Georgia Institute of Technology, U.S.A.
E-Mail: manu.menon@gatech.edu

Jochen Teizer[*]
School of Civil and Environmental Engineering, Georgia Institute of Technology, U.S.A.
E-Mail: teizer@gatech.edu

Charles Eastman
College of Architect, Georgia Institute of Technology, U.S.A.
E-Mail: charles.eastman@coa.gatech.edu

*Corresponding author.
E-mail address: teizer@gatech.edu
Telephone: 404-894-8269
Fax: 404-894-2278

Integrating BIM and Safety: An Automated Rule-Based Checking System for Safety Planning and Simulation

Abstract

Safety planning in the construction industry is generally done separately from the project execution planning. This separation creates difficulties for safety engineers to analyze what, when, why and where safety measures are needed for preventing accidents. Lack of information and integration of available data (safety plan, project schedule, 2D project drawings) during the planning stage often results in scheduling work activities with overlapping space needs that then can create hazardous conditions, for example, work above other crew. These space requirements are time dependent and often neglected due to the manual effort that is required to handle the data. Representation of project-specific activity space requirements in 4D models hardly happen along with schedule and work break-down structure. Even with full cooperation of all related stakeholders, current safety planning and execution still largely depends on manual observation and past experiences. The traditional manual observation is inefficient, error-prone, and the observed result can be easily effected by subjective judgments. This paper will demonstrate the development of an automated safety code checking tool for Building Information Modeling (BIM), work breakdown structure, and project schedules in conjunction with safety criteria to reduce the potential for accidents on construction projects. The automated safety compliance rule checker code builds on existing applications for building code compliance checking, structural analysis, and constructability analysis etc. and also the advances in 4D simulations for scheduling. Preliminary results demonstrate a computer-based automated tool can assist in safety planning and execution of projects on a day to day basis.

Keywords: Building Information Modeling, Prevention through Design, Planning, Rule Checking, Safety, Simulation.

1. Introduction

Problems in Safety Planning, Design, and Execution

It is widely recognized that the construction industry is still different than most other industries in regards to customization, on-site fabrication or assembly, and number of trades present to execute work tasks. Some practitioners even claim that construction sites are often under resourced and under planned (Egan, 1998). The utilization of and collaboration among staff, for example, is often key in operating a site effectively. Any tool or practice that can make work tasks easier, will be helpful in reducing errors and waste (time, cost), and ultimately lead to better process and work flow efficiencies.

A key for successful projects in all industries is safety. As good safety practices and records can create a positive, pro-active, hazard free, and productive work environment, planning for safety at the front-end of a project is essential (Waly, 2002). However, construction remains at high rates of accidents and fatalities. Existing safety culture and management focus on planning for safety, applying best practices, and providing personal protective equipment (PPE). It is believed (Teizer et al. 2010) that technology can play a key role in reducing incident rates further once it positively influences current practices in safety planning, such as manual or experience-based decision making.

Current Methods

Although federal and state regulations and standards, and company best practices assist the decision making process of construction safety managers, research has shown that safety extends beyond just the application and adoption of rules. Creating a "safety culture" is needed (Hinze and Wiegan, 1992). It is further suggested that safety planning must also be conducted prior to a construction activity for determining the safety measures that are needed. Planning for safety is a first but fundamental step for managing safety. Construction site safety often remains the sole responsibility of the contractor. Failure or limited expertise of staff for good safety planning lead to increased safety risks, for example, exposing workers directly to hazards. In addition, limited attention is given to safety during design phase of a project. To date, the cooperation and communication among project stakeholders (owners, contractors, subcontractors, etc.) in regards to safety is quite limited at the front-end. Furthermore, safety planning in construction is generally performed separately from the project execution planning. Staging work tasks properly and safely often happens late in the process of getting a work site organized, and often is dependent on experience of safety engineers or staff involved. The separation of work task and safety planning creates an additional difficulty for safety engineers to analyze what, when, why, and where safety measures are needed for preventing accidents (Chantawit et al., 2005).

Issues during Design and Planning Stage

Major problems in current safety planning system are that design choices often determine construction methods and schedule. Often designers do not understand the impact their work has on construction methods, schedule, and most importantly on safety. Little knowledge and transparency exists during the design stage what the potential hazards could be once a project task is executed, and what prevention plans/methods may be applied to resolve the safety issue. Often, the relationship of planning for safety and work task execution is weak; for example, many contractors use two-dimensional drawings (2D) to determine hazard prevention techniques. Current practices cause difficulties in using and analyzing potential alternatives in safety planning. Even with full cooperation of all related stakeholders, current safety planning and execution still largely depends on manual observation and past experience. The traditional manual observation is labor-intensive, time-consuming, and thus inefficient and the observed result can be error-prone due to subjective judgments.

Reasons for an Automated Rule-based Safety Checking System

Other good reasons for assisting safety management in construction with automated safety tools have been stated in research: (1) The planning and design phases provide a vital opportunity to eliminate hazards before they appear on the site; (2) the ability to eliminate hazards diminishes as the project progresses (Gambatese et al., 2007).

Since safety rules, guidelines, and best practices already exist, they can be used in conjunction with existing three-dimensional (3D) design and schedule information to formulate an automated safety rule checking system to detect hazards automatically, visualize their location in a virtual 3D space, and provide solutions and visuals of protective systems to mitigate the identified hazards. Such a system can also function as a tool for simulating and visualization progress on project and safety over time. In particular the indication of safety measures will help safety managers planning for safety upfront during the design phase, but also during the construction stage, when preparing safety work tasks, controlling and monitoring for safety during the construction phase (Benjaoran and Bhokha, 2010).

2. Background on Information Modeling and Safety

BIM and VDC

Building Information Modeling (BIM) along with Virtual Design and Construction technology (VDC) have been highlighted by the Architecture, Engineering, and Construction (AEC) industry. BIM can provide a powerful new platform for developing and implementing "prevention through design" concepts that can facilitate both engineering and administrative safety planning and control tasks at the design and construction stage of a project.

Information modeling-enabled virtual safety controls can be used to detect potential safety hazards ("clashes"). Virtual design and construction can simulate various stages of the construction process to allow engineers, architects and contractors to identify potential safety and health hazards at an early stage in the project. Creating alerts and finding mitigation means and methods has the potential to resolve most if not all safety and health hazards up front.

Rule-based Checking Systems

Rule-based checking systems have been developed for building models as part of the new BIM technology (Eastman et al. 2009). They have been used to check fire exits and American Disabilities Act requirements, and are slowly growing to address other areas. The most widely used application in construction might be "clash detection" tools in BIM software (e.g., to detect design conflicts of structural components). Rule-based checking systems for construction safety applications have also received attention. Both Solibri and EPM (Engineering Planning Management) technologies, for example, have such

capabilities in their software platforms. However, they are lacking one or more of the following capabilities:

1. Identification and machine-readable safety rules that can be checked in the context of a 4D safety simulation.
2. Definition and structure of safety information to allow different types of safety checks (e.g., from simple fall protection of slab edges to complex spatio-temporal work-space occupation analysis).
3. A rule checking language using predicate logic/types of rules that can easily be checked by a computerized tool.
4. An execution structure that can find all safe/unsafe conditions in a building.
5. An optimized reporting and visualization structure.

Information and Communication Technologies in Construction Safety

3D visualization and 4D simulations increase the ease and level of understanding of construction processes. They facilitate better communication among project stakeholders. These features are inherently embedded in BIM and thus can enable more effective safety planning before and during construction. Such technology can enhance safety through automated hazard identification early in the process, and propose inexpensive and easier ways to solve safety clashes. Utilization of BIM technology thus can bring safety more closely to the construction planning phase.

Previous work that has been developed offers a range of new safety tools to help contractors during the design and construction phase. Information and communication technology, such as BIM, virtual reality (VR), Geographic Information Systems (GIS), online database etc., are applied for site hazard prevention and safe project delivery.

Hadikusumo et al. (2004) adopted VR for construction safety by creating a design-for-safety-process (DFEP) database. The VR-based DFEP tool helped to identify safety hazards during the building design phase. The Virtual Construction Laboratory (VCL), developed by Li et al. (2003), is a knowledge-based VR system that enables a planner to conduct virtual experiments with innovative construction technologies and processes. Compared with other VR based real-field construction management systems, it provides more interactive capabilities to mock-up different construction scenarios rather than mere visualization and dynamic navigation of a construction site. Zaki (2006) developed the Patterns Execution and Critical Analysis of Site Space Organization (PECASO). It aims at developing a methodology and tool to assist planners with the assignment of activities' in the execution space, as well as the identification and visualization of workspace congestion. Benjaoran and Bhokha (2010) developed an integrated system for construction and safety management based on 4D CAD model and some rule-based algorithms (Hazard Explorer and Safety Measure Advisor). While the automated approach with hard-coded algorithms does not consider complex design parameters, reliance on human is still needed to check for safety rules. VTT Technical Research Centre of Finland (2010) developed a manual procedure of using BIM technology for safety planning, management, and communications. As part of the 4D-construction safety

planning, VTT visualized BIM-based 4D safety railings for fall/edge protection in Tekla Structures.

Compared to other work related to BIM and safety, our research provides novel intelligent functionality of a fully-automated rule-based safety checking system for building information models (BIM).

3. Research Objectives

Collecting and analyzing construction resource location and project data (schedule, work breakdown structure, resource allocation) can be linked to a building information model (BIM) to generate a rule-based safety framework that enables safer design, planning, and execution of work tasks. At the same time, data fusion of safety rules and geometric project data can create information, that once applied will create knowledge that can improve safety education and training at the planning/design and construction stage. The objectives of this work are as follows:

1. Develop a framework that integrates safety rules with BIM.
2. Develop a rule-base consisting of object oriented/logic for safety evaluation.
3. Implement the rule-based framework and verify it on a selected case study.

To limit the scope of our work, we focused on fall protection. Falls in floor openings and from roof edge can result in serious injury and very often lead to death of workers. Falls to a lower level are the largest single source of fatal injuries for construction workers, and accounted for 33% of all construction fatalities in 2005. In OSHA's Handbook (29 CFR), fall protection is required in work spaces such as ramps, runways, and other walkways; excavations; hoist areas; holes; formwork; leading edge work; unprotected sides and edges; overhand bricklaying and related work; roofing; precast erection; wall openings; residential construction; and other walking/working surfaces. Deciding what fall protection system to apply, where, and when are an important task, and thus part of the research questions that is to be answered.

4. Framework and Methodology

Although the future might develop a more comprehensive open source repository for safety rules and regulations, an initial set of rules that is to work with any safety rule checker in BIM can be generated from OSHA guidelines and industry best practices (Sacks et al., 2009).

The proposed rule-based safety checking system is illustrated in Figure 1. The first step is to collect and analyze construction data to schedule, work breakdown structure, resource allocation. This data can then be linked to a Building Information Model (BIM) using an automated rule-based safety framework that enables safer design, planning, and execution of work tasks. As construction schedules change frequently, 4D simulation will be

updated and re-run. Rules will be extracted and coded from the construction standards information identified in the Occupational Safety and Health Administration (OSHA) codebooks and any local construction safety best practice. The association between schedule and building model are one-to-many (e.g., sheet-rock finishing of multiple walls in a room), and many-to-one (e.g., formwork, reinforcement placing, concrete pouring to complete work on a reinforced concrete wall). Data fusion will create valuable safety information that once updated and applied frequently will become knowledge for all project stakeholders. Knowledge will ultimately lead to improvements in safety education and training at the planning, design, and construction stages.
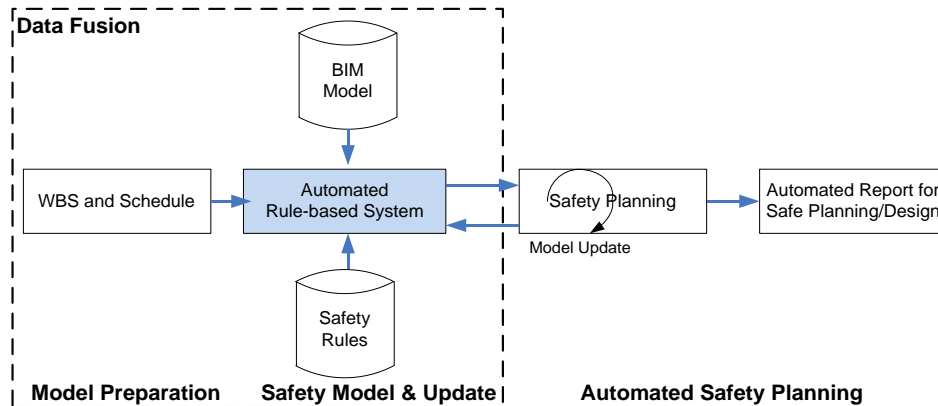

Figure 1: Framework for implementing an Automated Rule-based Safety System

5. Developing a Rule Base for Virtual Design and Construction

Object-oriented and Logic Repository of Safety Rules

According to OSHA regulations, fall protection rules can be classified into three parts: (1) Definition, (2) general requirement, and (3) prevention criteria. Definitions specify An extensible repository of rules has to be developed for the purpose. An initial set of rules was generated by using the OSHA guidelines. This set can be extended in the future into a comprehensive open source repository for organization-based safety rules and regulations. We implemented an automated rule engine based methodology to check the Building Information Models for compliance with such a repository. By making this extensible, we provided an opportunity to learn and train the rule engine model based on initial results. This can also include new sets of rules and object types in the database. Such a machine learning approach is commonly used in the industry, as computational programs tools are much more efficient than humans in applying a rule based checker. the unsafe area; general requirements show the protection methods which should be applied in a specific scenario; and prevention criteria relates to the detailed information of the prevention system to be used.

The preliminary research work concentrated on prevention falls from openings in slabs, edges on floor, and openings in walls. According to OSHA a "hole" means a gap or void of two inches (5.1 cm) or more in its least dimension, in a floor, roof, or other walking/working surface. Regardless of length, we implemented a default guardrail system for edges of slabs, floors, or for openings in walls, if they were elevated more than 1.8 meters (six feet). For holes measuring more than one meter (user-defined; 40 inches) in its least dimension in a floor, we applied also a guardrail system. Holes were "covered" if an opening measured less than one meter but more than five centimeters in its least dimension. Holes with less than five centimeters (two inches according to OSHA) in its least dimension were ignored (due to the small size of the hole). The default table-based safety rule translation for fall protection is shown in Table 1.

Table 1. Example of table-based rule translation for holes in concrete slabs.

Length (x) of a Floor Opening in its Least Dimension	*Prevention Method*
< 5 cm	*"Not considered"*
5 cm < x < 1 m	*"Cover with panel"*
> 1 m	*"Apply a guardrail system"*

Appropriate Software for Implementing Rule Engine and Model Checking

Tekla Structures, a BIM-based structural engineering and modeling software, provides construction management functions such as 4D simulation, site layout planning, quantity-take-off function and etc. Taking advantage of Tekla's embedded functionality and its OpenAPI, we first developed our automated rule-based safety checking system in Tekla. In a second approach, we utilized our rule-based safety checking system in the Solibri Model Checker (SMC). SMC is an (industry foundation class) IFC-based model viewer that allows complex rule checking capabilities. We implemented a translator to convert syntax-based rules into machine-readable equations. To date, such safety code and parameters to check every building object in BIM for safety are not available in any commercially existing BIM software.

6. Case Study: Automated Rule-based Safety System for Fall Protection

Implementation in Tekla

The OpenAPI in Tekla makes it possible to build a project with pre-fabricated model elements virtually. The object library contains parametric components that automate the tasks of creating the details and connections of the model. The OpenAPI makes it further possible to integrate further functionalities with the 3D model and continually enhance new features and attributes.

A 3D model was created in Tekla showing a construction site in progress. The building information model included different types of openings that could be a potential fall hazard. The identified openings had different sizes and geometric shapes (polygonal,

rectangular, and circular). The holes were located on walls and floor slabs. The model (see Figures 2, 3 and 4) shows a four-story building with walls on the first two floors, spiral and emergency staircases, and pipework that are potential trip hazards.

Taking advantage of Tekla Structure and its OpenAPI, the rule-checking steps are listed as follows:

    a. Automatically check the model and detect holes in slabs and exterior walls, and edges of slabs;
    b. Differentiate the opening in slab from wall openings (including windows);
    c. Install guardrail system at floor edges/wall openings and cover floor opening;
    d. Take-off quantity and type (leading to an estimate) of the protection safety system to be installed;
    e. Provide update in schedule of when and what safety protective system needs to be installed; and
    f. Create a 4D visualization and 3D virtual environment to visualize the protective system and how it fits in the construction schedule/sequencing.
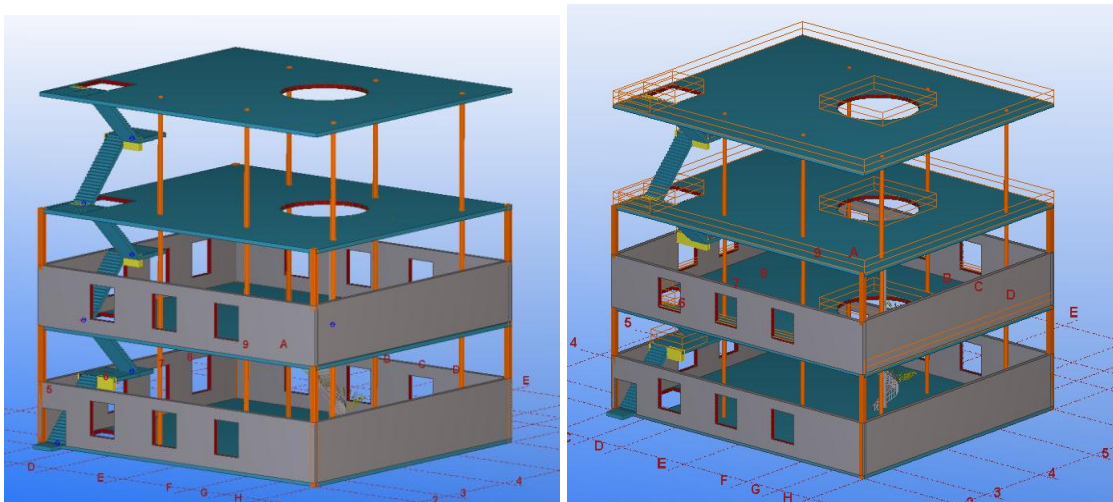
(a) Modeling w/o protective system   (b) Modeling w protective system
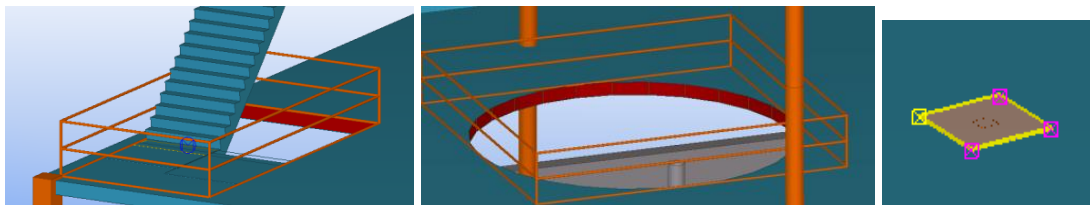**Figure 2:** Automated rule-based fall protection detection and installation in Tekla

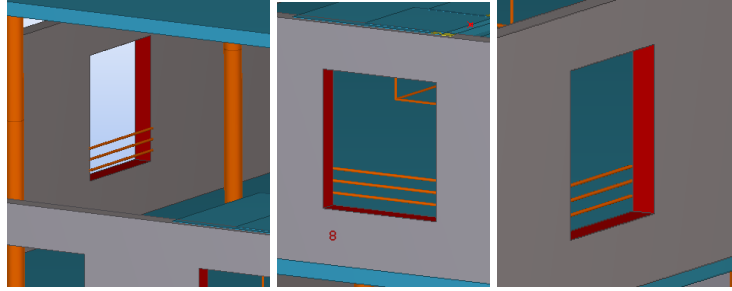**Figure 3:** Examples of floor openings with different shapes/dimensions and protection.

Figure 4: Examples of exterior wall openings and guardrail protection system in place.

Implementation in Solibri Model Checker

Similar implementation and results of opening and edge detection, quantity-take-off and 4D simulation were realized in the Solibri Model Checker (see Figure 5 and 6). Apart from that, rule customization is enabled and allows the user to select alternative protection systems. These individual prevention methods can be selected in a drop down menu (see Table 2). For example, the identified hazard #45 (a rectangular opening in a floor slab) was on the second floor level, had a width of five and four meters in length and width, respectively, with a height distance of three meters to the next floor, covering an area of 20 m^2, and having a circumference of 18 m. The system automatically applies user- or OSHA-defined best practices, in this case, proposes a "Guardrail system/safety fence". The user could still selected another protective system, thus the developed approach takes advantage of human knowledge and experience.

Table 2. Detailed information for each opening and its customized prevention method.

Hazard No.	Floor Level	Max. Hole Length	Max. Hole Width	Dist. To Lower Level	Hole Area	Hole Perimeter	Selected Prevention Method*	Check List √ / □
45	Level 2	5 m	4 m	3 m	20 m^2	18 m	"Guardrail"	□

* Select in a drop-down menu from "Not applicable", "guardrail system", "cover", "personal fall arrest system", or user-input (e.g., "safety net").
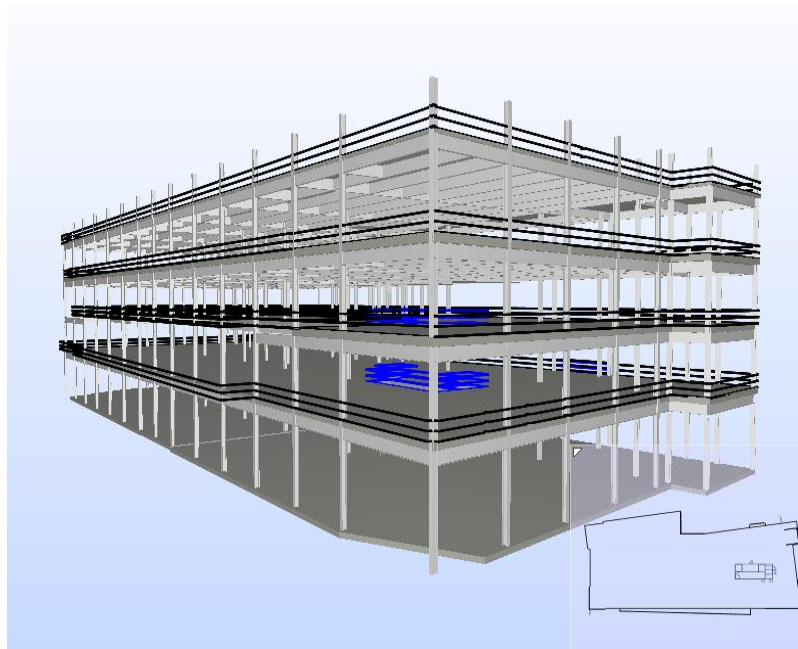
Figure 5: Fully-automated slab opening and edge detection with application and three-dimensional visualization of protective solutions.
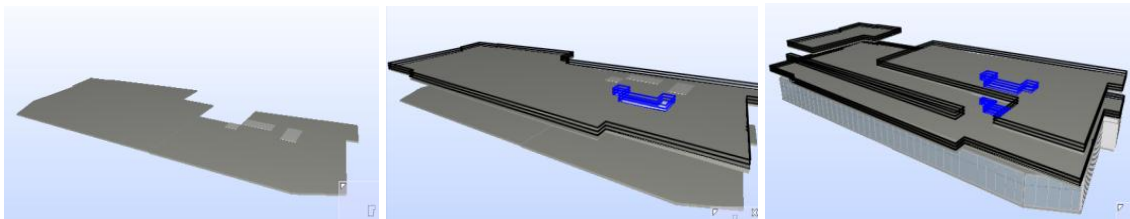

Figure 6: Schedule-based safety visualization and simulation (Phases 1, 2, and 3).

Results and Comparison

Preliminary results indicate that fall protection rules in OSHA can be translated into machine readable rules that then can be applied in the developed automated safety-rule checking tool. The automated rule-based safety checking system has been successfully implemented on a sample model for fall protection. The application of other (and more complex) rules might be considered in future research. This performed work illustrates that safety planning can be considered in the design stage for early detection and application of protective safety system, including identification of hazard location, quantity take-offs, and schedule for implementation of protective safety systems.

Implementation of the safety-rule checker in two software environments was conducted. The Tekla Structure software can easily add new (safety) objects (e.g., guardrails and covers). Tekla also possesses an OpenAPI that allows visualization, quantity-take-off and 4D simulation. Further advantages are envisioned once the developed safety-rule checker is embedded in the existing construction management tool. The Solibri Model Checker is an IFC-based model viewer and checker that offers easy-to-use visualization and virtual walk-through functionality.

7. Conclusions and Future Work

An automated table-based safety rule translation prototype was developed based on OSHA rules and construction safety best practices. The developed tool ran on two technology platforms: Tekla Structure and Solibri Model Checker (SMC). Preliminary results demonstrate the feasibility of the developed safety rule-checker in both software applications.

The developed automated safety-rule model checker shows good capability of practical applications in building information modeling and planning of work tasks. Once applied in construction design and execution phases, it may possess a large potential for reducing errors and waste in safety planning for construction site work sequences and activities. From a safety management perspective, time and effort of safety staff/engineers can be saved through an automated safety code checking and simulation tool that assists labor-intensive safety tasks. For example, hazardous work spaces can be identified and potential hazards can be prevented already at the design stage, before any field work is started.

Future work may focus on research that studies the applicability and performance of the safety-rule checker in simple to complex building information models. The analysis of parametric and complex rules customized to the specific type of project might also be explored. It is envisioned that the implementation of the safety prevention methods might need to be adapted to the scope of the project, type of firm, and the design process. Lessons and experiences can be learned to improve the tool further. Research will also need to focus on additional cases studies, scenarios, and machine-readable safety rules, guidelines, and best practices to convince practitioners of its usefulness.

References

A.F. Waly, W.Y. Thabet, (2002) A virtual construction environment for preconstruction planning, *Automation in Construction* 12 139–154.

B. H. W. Hadikusumo, Steve Rowlinson, (2004). Capturing Safety Knowledge Using Design-for-Safety-Process. *Journal of Construction Engineering and Management*, 130(2), 281-289.

K.K. Sulankivi, K.; Mäkelä, T.; Kiviniemi, M. , (2010) Critical space analysis 4D-BIM for Construction Safety Planning, in: P. Barrett, Amaratunga, Dilanthi, Haigh, Richard, Keraminiyage, Kaushal & Pathirage, Chamind (Ed.), *CIB*, Manchester, 2010.

Census of Fatal Occupational Injuries Summary, 2009. U.S. Bureau of Labor Statistics. 19 Aug. 2010. Web. 01 May 2011. <http://www.bls.gov/news.release/cfoi.nr0.htm>.

Chantawit, D., Hadikusumo, B.H.W., Charoenngam, C., (2005). 4DCADSafety: visualizing project scheduling and safety planning. *Construction Innovation*. 5, 99–114.

Eastman, C., Teicholz, P., Sacks, R. and Liston, K.,(2008), *BIM Handbook*, John Wiley & Sons, Inc. USA.

Eastman, C., J. Lee, Y. Jeong, and J. Lee, (2009). Automatic rule-based checking of building designs. *Automation in Construction*, 18(8), 1011¨C1033.

Egan, J., (1998), Rethinking Construction, Scope for Improving the Quality of UK Construction, Construction Task Force Report, *Construction Task Force*, London.

Gambatese, J., Behm, M., Rajendran, S., (2007). Design's role in construction accident causality and prevention: perspectives from an expert panel. *Safety Science* 46 (4), 675–691.

Heng Li, Zhiliang Ma, Qiping Shen, Stephen Kong, (2003), Virtual experiment of innovative construction operations, Automation in Construction, 12(5), *Computer Aided Architectural Design Research in Asia*, (9), 561-575.

Hinze, J., Wiegan, F., (1992). Role of designers in construction worker safety. *J. J. Constr. Eng. Manage*. 118 (4), 677–684.

Mallasi, Z. (2006). Dynamic quantification and analysis of the construction workspace congestion utilising 4D visualization. *21st International Symposium on Automation and Robotics in Construction*, Elsevier, 640-655.

Sacks, R., O. Rozenfeld, and Y. Rosenfeld, (2009): Spatial and temporal exposure to safety hazards in construction. *Journal of Construction Engineering and Management*, 135, 726.

Safety and Health Topics: Fall Protection. Occupational Safety and Health Administration - Home. Accessed May 2011. <http://www.osha.gov/SLTC/fallprotection/index.html>.

Vacharapoom Benjaoran, Sdhabhon Bhokha, (2010). An integrated safety management with construction management using 4D CAD model, *Safety Science*, 48(3), 395-403.