
ISSN: 2321-2152
IJMECE
International Journal of modern electronics and communication engineering
E-Mail
editor.ijmece@gmail.com
editor@ijmece.com
www.ijmece.com

ISSN2321-2152www.ijmece .com
Vol 5, Issue 3 Aug 2017

BIM-based fall hazard identification and prevention in construction safety planning

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ABSTRACT
The applications of Building Information Modeling (BIM) in building design and construction planning are growing rapidly. BIM-based modeling and 4D simulation (3D and schedule) has brought many benefits to safety and logistics applications as well. However, only limited automation in modeling and planning safety processes has been exploited so far. The objective of this study is to investigate how potential fall hazards that are unknowingly built into the construction schedule can be identified and eliminated early in the planning phase of a construction project. A survey of research on construction safety and BIM is presented first. Then, a framework was developed that includes automated safety rule-checking algorithms for BIM. The developed prototype was tested using models including an office and a residential building project in Finland. The first case study highlights the comparison of manual vs. auto-mated safety modeling of fall protective systems. It also describes the details to multiple design and as- built scenarios where protective safety equipment is modeled. The second case study presents results of applying the framework to the project schedule. It specifically simulates fall hazard detection and pre- vention. The contribution of this work is an automated rule-checking framework that integrates safety into BIM effectively and provides practitioners with a method for detecting and preventing fall-related hazards. Presented are also discussions of open issues regarding commercialization of the developed pro- totype and considerations which explore what impact it might have on resolving safety issues in the field by extending traditional safety management practices.

Keywords: Building Information Modeling Construction safety rule and code checking Fall hazard prevention Planning, scheduling, and simulation Prevention through Design

Introduction

Workplace injury, illness, and fatality statistics indicate occupa- tional health and safety (OHS) in building construction remains a worldwide problem. More than one third (36%) of all US workplace fatalities occur in the construction industry. Similarly, the Finnish construction industry is responsible for one out of four fatal

occupational accidents. Similar to several other industries, safety planning has a key position in the field of production planning. However, in the building construction industry safety, planning is carried out separately from the project design and planning phase. Even though falling from heights remains a major safety risk at construction sites according to

the US Bureau of Labor Statistics (2012), the fall protection plan typically is not created until con- struction starts in most of the existing projects (Sulankivi et al., 2010). Additional problems arise when detecting and resolving safety issues during the construction planning phase. For example, safety communication at the worker level is particularly challeng- ing under the harsh (weather, uniqueness) and dynamic (multiple resources, time constraints) conditions that exist at construction projects. Several previous studies reported similar issues (Goodrum and Gangwar, 2004; Hallowell and Gambatese, 2009; Benjaoran and Bhokha, 2010).

One of the major obstacles to effective safety planning is that traditional safety planning still largely relies on paper-based 2D drawings and schedules to understand the needs for safety equip- ment on a construction site (Chantawit et al., 2005). In terms of fall protection, Fig. 1 presents an

example of a traditional fall protec- tion plan where various fall prevention systems have been marked into a construction plan with different colors (Kiviniemi et al., 2011). Such manual fall hazard identification and planning relate to several inefficiencies. Some of these are:

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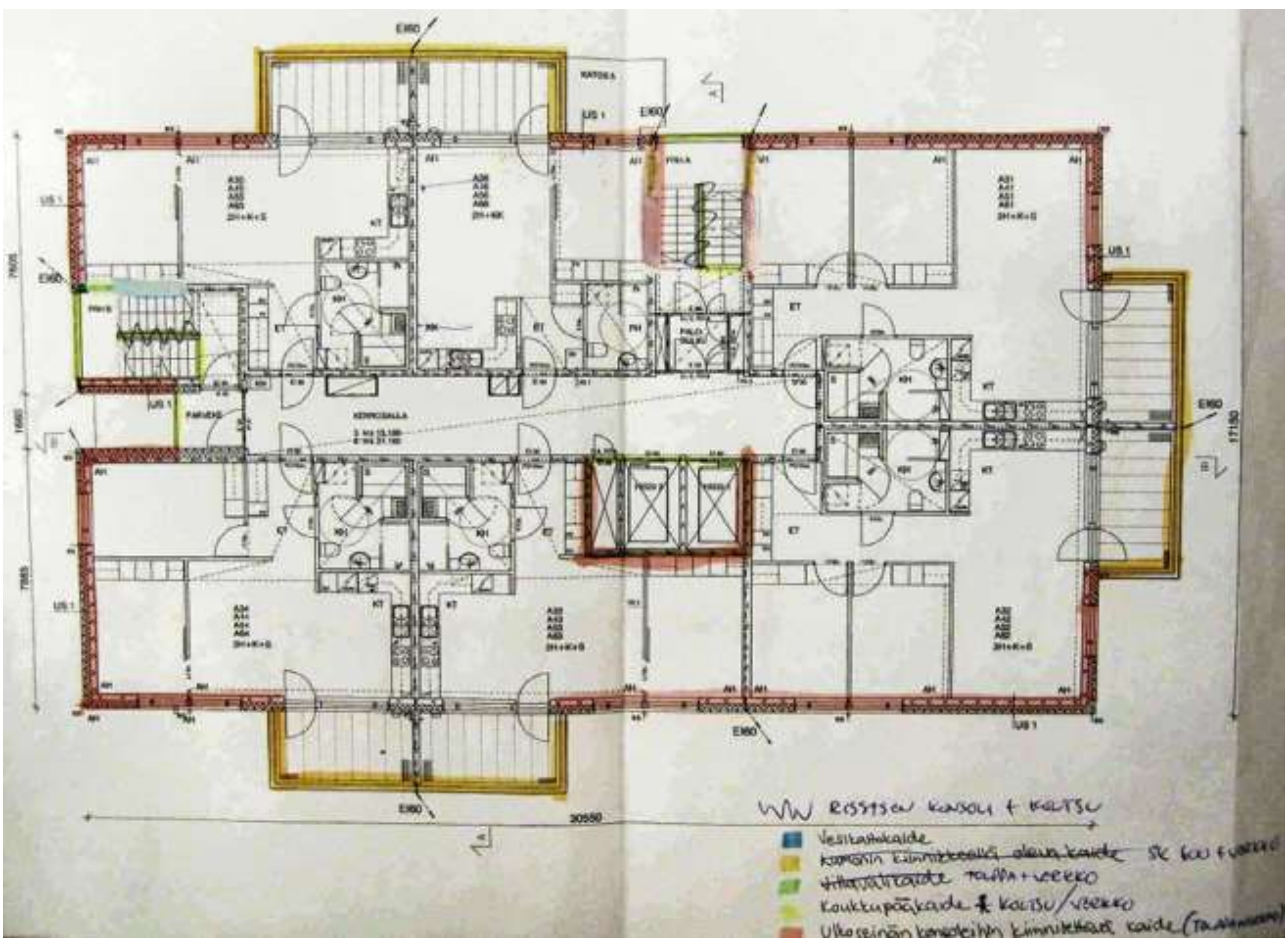
It requires professional safety engineers to detect potential safety hazards and determine safety equipment based on their experiences.
Many of the safety issues are implicit, being the result of par- tially complete conditions not shown on the building plans.
The dynamic nature of the construction project results in changes in safety needs. It is difficult to identify the potential fall hazards at different construction stages/schedules based on static drawings.
Construction schedule is subject to change based on various conditions such as weather, material delivery, which leads to change in the safety plan. It is time-consuming and labor-intensive to update the safety plan every time schedule changes.
Falls of humans to a lower level at a leading edge are easier to
recognize than smaller holes that cause foot injury, for example. These holes are hardly or never drawn in paper-based plans and thus might never be detected, even by experts.



Inefficiencies are witnessed in the current methods which are utilized for processing and reporting safety and health related issues on a construction project (Abraham et al., 2004; Egan, 1998). Technology that assists construction safety experts in the task of easier recognizing and resolving safety hazards while addressing the complexity and dynamism of jobsite conditions (Ku and Mills, 2010) can lead to safer construction with less effort.

Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition (National BIM Standard, 2013). The growing implementation of BIM in the Architecture/ Engineering/Construction (AEC) and Facilities Management (FM) industry is changing the way safety can be approached (Zhang et al., 2013). The application of BIM is currently increasing rapidly in construction operations planning and management and also in safety management. One starting point is to emphasize safety aspects early on in the building design and engineering phases (Zhou et al., 2012). Zhang et al. (2013) also pointed out that the con- struction industry is in need of addressing the inefficiencies of exist- ing paper-based and manual safety processes currently in use.

BIM-based methods are being applied in construction design and planning. They are also being implemented more and more in site safety management and supervision (Kiviniemi et al., 2011; Downey, 2012). Manual safety

checking generally follows a process like: (1) use the construction schedule to identify the construction actions and sequences or work tasks within the spatial layout of the project; (2) identify temporary conditions that create safety hazards; (3) plan corrective actions to eliminate safety hazards; and (4) integrate these corrections into the sche- dule. However, the limited human cognitive skill to mentally sim- ulate complex future conditions suggests that a more proactive and simulation based method using predefined pattern checking could greatly strengthen the effectiveness of this sequence of activ- ities. As stated by Kiviniemi et al. (2011), only an integrated approach will succeed in providing the competence of all domains. Based on previous research efforts (Zhang et al., 2013), this study aims to develop an automatic BIM-based fall hazard identi-fication and planning tool that (1) identifies potential fall hazards dynamically based on the construction schedule, (2) assists labor-intensive modeling and planning tasks of fall prevention sys- tem effectively, and (3) improves workers' safety awareness by visualizing the potential hazards. This case study also aims to eval-uate possibilities, benefits and development needs for automated safety code checking and planning. Also, we examine the usability and maturity of the developed BIM-based prototype tool that sup-
ports fall prevention planning in building construction projects.

The paper is structured in the following way: Section 2 presents a literature review on traditional hazard mitigation approach and the application of information modeling in construction safety plan- ning. In Section 3, the developed safety rule-checking prototype and its computational algorithms are introduced. Section 4 presents the application of the prototype in two case studies. Manual model- ing and automated modeling of fall protective system are discussed in the first case study along with the comparison between the design and as-built scenario. In the second case study, the dynamic characteristics of fall hazard detection and prevention generated by the prototype are shown as it is applied to a construction schedule. Section 5 shows a comparison of several BIM applications for con- struction safety planning. A summary and discussion of the findings and contributions are in the final section that concludes the paper.

Background

Traditional risk analysis and hazard mitigation

Hinze et al. (2013) investigated the effectiveness of using his- torical information. For instance, he reviewed OSHA recordable injury rates, to increase construction projects safety performances. Using leading predictors of safety performance, measures that can be used as predictors of future levels of safety performance, has been found to be a worthwhile alternative to leverage historical information. Safety indicators or safety risks analysis are critical processes to prevent construction safety accidents from happen- ing. Rozenfeld et al. (2010) developed ''Construction Job Safety Analysis'' to identify potential loss-of-control events and to assess their probabilities of occurrence. Shapira et al. (2012) developed an overall safety level index due to the operation of tower cranes. Instead of considering the use of tower cranes on a general con- struction site this added a factor that personalized the safety level to specific sites. Hallowell and Gambatese (2009) developed safety risk levels quantification method for concrete formwork construc- tion. Although researches have concentrated on developing safety risk levels using technology pro-actively (Teizer et al., 2010, 2013; Cheng et al., 2011; Cheng and Teizer, 2013), no practical approaches exist to date on how the data can be used by practitio- ners in the industry and with BIM. Hence, it is important to inves- tigate more advanced methods to integrate this information.

Information modeling in construction safety planning

Emerging technologies including database, computer-aided simulation and visualization provide new opportunities to enhance
safety planning. Many of them have their origin in traditional safety research. For example, Gambatese et al. (1997, 2008), Gambatese and Hinze (1999), Gibb et al. (2004), Choudhry et al. (2007), Toole and Gambatese (2008), and Lingard and Wakefield (2012) have contributed fundamental studies towards Prevention through Design (PtD) in operational safety and health in construc- tion (OHSC). These research efforts motivated other researchers, and even further, more advanced approaches in developing or applying emerging technologies to OHSC.

Hadikusumo and Rowlinson (2002) developed a design-for-safety-process (DFSP) tool to assist a user in identifying safety haz- ards which are inherently embedded in construction components and processes. The DFSP database contains building objects, asso- ciated potential safety hazards, and possible accident precautions database. Benjaoran and Bhokha (2010) introduced an integrated system for safety and construction management using an existing 4D computer-aided design (CAD) model. Guo et al. (2013) devel- oped a conceptual framework of adopting virtual prototyping tech- nology to aid in construction safety management. It consists of three components: modeling and simulation, the identification of unsafe factors, and safety training. Zhou et al. (2012) explored the implementation of visualization technology for safety manage- ment and risk assessment in metro construction. However, more advanced and efficient method needs to be explored to achieve both safety hazard identification and visualization along with the construction progress.

BIM has been rapidly recognized to change the process how construction projects are delivered. It has also been realized that BIM can be utilized to promote safety management, and combine safety with other construction planning processes. Turner Con- struction (Downey, 2012) established a standard, model-checking procedure to ensure their projects compliance with rigorous stan- dards of safety. Their BIM specialists developed a rule set package based on Solibri Model Checker (SMC) (Solibri, 2013). The VTT Technical Research Center of Finland (Kiviniemi et al., 2011) has developed a detailed framework for fall protection modeling and 4D visualization. The work includes the modeling of the temporary safety structures and equipment needed to carry out safe construc- tion work. It also models the permanent installation of safety equipment in a building for the construction, operation, and main- tenance phase. Attempts have also been made to unfold best prac- tices to improve collaborative planning procedures among general contractor, designers, and subcontractors. These existing studies certainly paved the road for improving safety planning and hazard identification using BIM, while compared to manual Beside automated safety checking, there are capabilities to also model automatically the suggested fall protection, which can be a very labor intensive task when using currently-available BIM- based software. Automated rule-checking on Industry Foundation Classes (IFC) model to assist fall protection has also been explored (Melzner et al., 2013). However, possibilities and current limita- tions of the developed framework by Zhang et al. (2013) are not known yet. Efforts are needed to investigate the applicability, limitations, and requirements of implementing such prototype to currently existing construction planning processes.

A significant shortcoming of the 4D approach identified by Zhou et al. (2012) is the dependence on computerized construction schedules. Construction operations are dynamic and subject to fre- quent changes that do not comply with originally scheduled work. Hence, digital schedules are rarely updated frequently to accu- rately reflect all operations underway at any given point in time. At the same time, safety modeling is suggested to be done with same level of detail as design and engineering of the permanently installed building parts (Kiviniemi et al., 2011; Sulankivi et al., 2013), which makes both the scheduling and model maintenance efforts more complicated. Additional safety knowledge, time, along with technical resource is needed in such BIM-based planning activities making it difficult in practical implementation. Thus, it is beneficial for practitioners to understand both the additional modeling requirements and the benefits of such a BIM-based safety hazard detection and prevention tool before it is applied in the field on a larger scale.

BIM-based rule-checking

Rule-checking approach

Existing safety rules, guidelines, and best practices can be used in conjunction with existing three-dimensional (3D) design and schedule information to formulate an automated safety rule check- ing system. The intention is to automatically identify these dynamic conditions, as the building is constructed, identify their location in a virtual 3D space, and interactively or automatically provide solutions and visualization of protective systems to miti- gate identified hazards.

process, more intelligent approaches are needed to provide safety rule checking in an automated and time-efficient manner.

Connecting safety management tasks into the 4D-model opens up entirely new chances to review and evaluate safety as part of construction operations. For example, it can increase cooperation in safety planning and enhance overall safety communication. 4D planning can create a safety planning practice that is undertaken earlier in a project than it would start in traditional construction projects. Furthermore, it can produce a more detailed safety plan- ning. Early safety planning, for example, might entail safety fea- tures to be modeled in 4D. Related to protection against falls, such modeling would be guardrails, protective covers and nets, and safety harness anchor points. Zhou et al. (2012) proposed a col- laborative approach that relies on 4D construction planning. They suggested new directions of research on construction safety and digital design, such as leveraging technologies to enable construc- tors to share their knowledge with designers and using the visual- ization technologies to bring knowledge of the construction site into design. Zhang et al. (2013) developed a BIM-based automated tool which can assist in detecting potential fall hazards including falling from leading slab edges, slab holes, and wall openings.

Such a platform developed by Zhang et al. (2013) can function as a tool for providing easily accessible and understandable visual- ization of up-to-date progress on construction and safety over time, and in particular, to detect dangerous hazard locations on the site. The indication of safety measures will help safety manag- ers planning upfront for safety during the construction planning phase, as well as during construction. The rule checking process consists of the following procedures:

Rule interpretation: The interpretation of safety rules from safety regulation or best practices (e.g., OSHA) is a logic-based mapping from human language to machine readable form. The name, type, and other properties in the rule can be analyzed and extracted from the written rule.

Building model preparation: A building model must be well constructed to include required objects, attributes, and relations used to carry out the rule checking. In addition, since the need of fall prevention equipment depends on the status of the construction work, a 4D model including the installation schedule/order of building assemblies is required.

Rule execution: The rule execution phase brings together the translated rule sets with prepared building model. The rule may apply to thousands of condition cases, requir- ing combinatorial tracking. The rule execution has two steps: (a) automatically check the model to identify unsafe conditions, and (b) identify and apply candidate solution actions to correct the unsafe condition. This last step can be variously controlled, manual intervention for each con- dition, to completely automatically resolve through the application of rules to determine the best correction.

Rule checking reporting: The checking results can be reported in multiple forms: (a) visualization of applied safety protective equipment in the model, and (b) Excel-based reports of unsafe conditions and the corrective actions taken. In addition, quantity-take-off information for resource leveling of safety equipment and importing the generated information into project schedules is also possible.

Safety correction: The primary corrective actions that will take place on construction sites are to schedule and track logistical movements of (safety) material based on the rule checking reports. An implementation in the field, for exam- ple, could be reports on a BIM platform that assign work tasks for the installation and removal of safety equipment on

a building floor.
This is an expansion from the general requirements needed for rule-checking systems (Eastman et al., 2009), in that the safety amelioration steps are included.

Applied rule-based algorithms in case study

Once the building information model has been well constructed and the connections between the model objects and the schedule have been established, rules can be applied for detecting safety hazards. The method of Zhang et al. (2013) is explained:

Slab edge protection: Fig. 2 explains the algorithm for detect- ing required prevention methods according to OSHA safety rules. For each task, it examines if slab objects are linked to a given work task. For each slab object associated with the task, the algorithm checks if the slab needs to be merged with existing slabs. If there is no existing slab on the same level, the slab boundary is computed. Also, existing wall ele- ments are detected to see if any part of the slab boundary does not need fall protection. Thus, unprotected edges which ed.
Otherwise, nd
overlapped e try
condition res ew
guardrails are ng
guardrails for
Slab hole pro to
detect slab ct-
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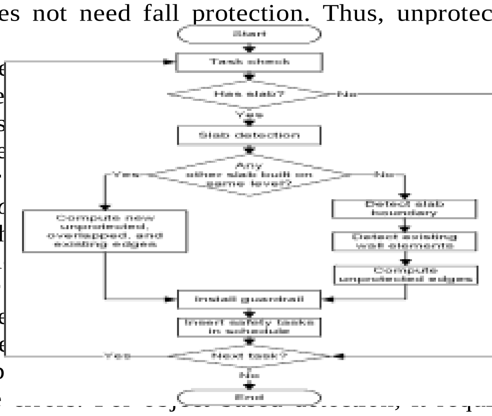


additional labeling efforts to assist hole recognition from other void objects in the model. In this study, we mainly rely on object-based object recognition but also check if it is a cut-through hole which create fall hazard by comparing the depth of the slab and the depth of the hole. Ideally, in order to clearly distinguish those two conditions, during

Fig. 2. The rule checking algorithm for detecting required prevention methods for slab edge.

the modeling stage, engineer would have two different tools/buttons to (a) create cut for complex geometry and (b) cut for actually slab cut through.
Wall opening protection: The wall opening detection process is similar to slab hole detection. The special situation to be considered is the location of the wall element: whether it is an interior wall or exterior wall. For the ones located at the edge of the slab, once the wall element has been
The idea was to plan the position of the guardrail posts at the slab edges so that they would not need to be moved during con- struction. This would both save time and reduce the risk of falling from heights. In case railings were close to concrete columns (see Fig. 4), the railing posts were positioned at a certain distance from the designed columns. The same safety railing solution was used at leading edges that had prefabricated holes in steel beams, which ensured rapid installation and removal of safety equipment (Fig. 5). The manually-generated BIM-based safety guardrail plan was delivered to the contractor together with some model views pre- senting the modeled solution for implementation in the field. Since the 4D scheduling for temporary safety equipment is complicated with current BIM modeling tools, the VTT research team visualized the fall prevention related to concrete and steel frame construc- tion, as well as scheduled and visualized the workflow for both the permanent building structures and any temporary safety equipment. Before the start of the actual pilot, functionality tests concerning the use of 4D BIM tools on the project were carried out. The test project was an office building that was originally modeled by the project's structural engineer in Tekla Structures. The results show that interactive 4D fall protection planning, espe- cially scheduling and visualization of safety railings, offers a feasi-
ble approach that is useful for practitioners in the field.
From a practical perspective, in order to realize 4D BIM-based planning and visualization of temporary structures, it requires some special requirement/settings for modeling and visualization. For example, in terms of 4D simulation, temporary structures need to be removed/hidden from the model after they are no longer needed.

installed, the guardrail for the slab edge protection can be removed, at the same time, wall opening if exists need to be protected. If there is no slab hole, for example a hole for an elevator shaft, close to the interior wall, the wall opening does not need to be considered or protected.

Lessons learned from case studies in BIM-based fall hazard detection and prevention planning

Case study 1: comparison of manual vs. automated modeling

In the first case study, fall protection equipment was modeled both manually and automatically for cast-in-place concrete in the basement of an office building. Benefits and limitations of both methods were compared.

Manual modeling of safety protective equipment:

In order to understand the complexity of modeling and plan- ning efforts of safety prevention system, manual modeling and planning was first conducted in BIM. Fig. 3 presents a photo and the modeled 3D safety railing components as it is typically used at Finnish construction projects. The selected guardrail solution for leading edges on slab surfaces consists of guardrail posts and timber railings. The 3D presentation of the customized safety components have been modeled manually. The realistic guardrail solution was based on best practice information contractors provided and used at the building site. The geometry of the posts corresponds to the Finnish Vepe product. The dimensions of the handrail, intermediary guardrail, and toe board correspond to the existing specifications.
Automated fall hazard detection and protection using rule-checking algorithms

Manual modeling of fall protection methods provides a good understanding of potential fall hazards on the construction site and comes typically with high level of detail. However, due to the time-consuming nature of manual modeling, an automated modeling approach is recommended. The system presented in this paper has been applied on the same pilot project. Fig. 6 illustrates the automated modeling results of the developed system on one floor of the basement.

Experience on manual BIM-based fall protective methods modeling

The fall hazard detection and prevention planning was carried out by modeling safety railings and floor opening covers in the structural model of the same office building. This planning was applied in more detail than the traditional manual planning had been carried out. The site staff guided the planning and modeling that was implemented by the research group. This planning and modeling was done three

months earlier than the start of the work phases. In the current planning practice, such detailed fall preven- tion planning is not carried out early in the project phase. Only the required safety equipment types are selected and procured, and a more general plan of fall prevention arrangements is presented.

Fig. 7(a–j) present how the model based fall prevention plans were implemented in the BIM and construction site. There are some visual differences between pictures due to slightly different viewpoints. Some pictures also show the models to the concrete formwork. While it influences the location of safety railings, its parts are modeled at a more abstract level than the safety railings. One current difference is that materials, equipment, and other temporal construction objects are not modeled in BIM. These objects, however, since they might be contributors for or cause incidents they should be modeled as well. It might be useful to

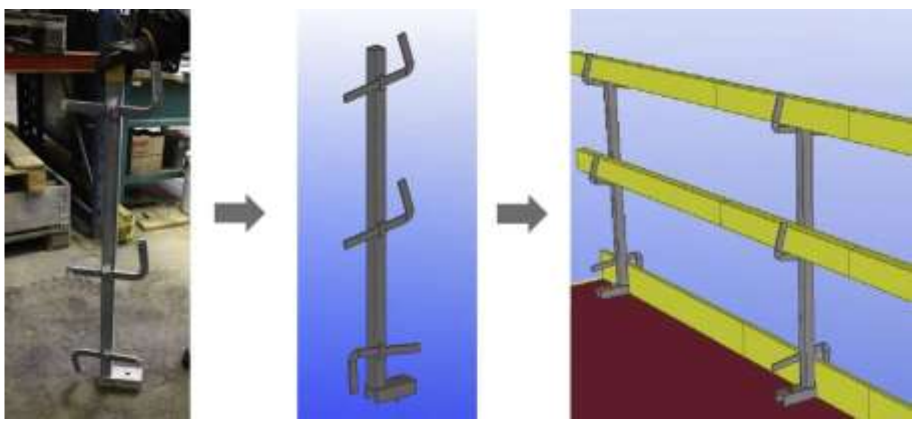
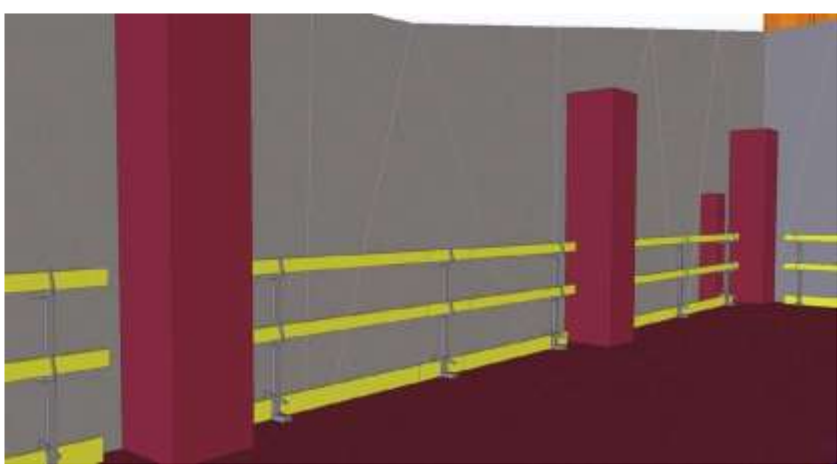


Fig. 3. Safety railing equipment modeled for the project (guardrail post for surface installation used together with timber railings).



\Fig. 4. BIM-based falling prevention planning: safety railings in edges of cast-in-place slabs (Kiviniemi et al., 2011).

Fig. 5. The same safety railing solution modeled into an upper office floor: guardrail posts installed to pre-designed holes in the prefabricated steel beams (Kiviniemi et al., 2011).

analyze also detailed work activity and space needs of trades which can be highly dynamic in nature. These issues are all not part of the scope of this paper.

The positions of the safety railings on the slab edge have chan- ged substantially compared to the plan (see Fig. 7(c and d)). The initial idea for the planned position was to allow installation of the wall elements behind the railings while they are near to the edge. During the implementation stage of the safety railings in the field, decision makers decided to position the guardrail further inside the slab so the railings created a continuous guardrail. A temporary stairway which was an emergency exit from the lower basement floors can also be seen in Fig. 8. This guardrail was not planned at the time of the modeling since other tools for scaffold- ing modeling are necessary (Kim and Teizer, 2014). A main reason for changing the positions of the safety railings was also that the floor area needed space for the three-legged shoring stands. Since the guardrail was moved inwards, the middle rail had to be removed. Another reason might have been that the latest BIM ver- sion of the structural model used during planning did contain sev- eral square holes for fixing façade elements to the slab edge. These holes limit the available area for the guardrail installation. In addi- tion, since the safety planning was done three months in advance of construction, the most recent changes might not have been implemented in the BIM. Therefore, detailed safety hazard detec- tion and prevention planning using BIM should always be close to construction and use the most recent and updated version of the BIM. Detailed BIM-based safety planning should be also done in coordination with all project stakeholders, in particular the sub- contractor who is eventually responsible for the safety equipment implementation. Other risks may arise similar to using other tools. A danger in managers thinking might be that the model is correct and therefore trusting it fully rather than using their skill and experience to manage the site processes.

Fig. 6. Automated slab edge and hole detection and guardrail installation results.

On many projects it can also happen that design and methods vary. The safety railing at the leading edge of the concrete slab (see Fig. 7(e and f)) show metal posts and wooden guardrails. How- ever, the implementation in the field shows an improvised solution that uses wooden posts. The deviation can cause serious safety issues if standards are not followed. Reasons of why the field deviated from the plan might need to be answered. Applying man-made safety equipment on site certainly does not follow a lean approach, unless the deviation was necessary to overcome unforeseen site conditions. Fig. 7(g and h) presents safety railings on one of the upper floors of the pilot project. A railing solution where the posts are attached with bolts to the thread sleeves in the steel beams had been used. Those fixings were welded to the steel beams already in the steel fabrication shop. They were already present in the structural model of the steel frame. The sleeves provide a fast and reliable fixing method for the railing posts. The selected process has the advantage for safe installation and removal of safety railings in particular during poor site condi- tions (i.e., weather).

The interior of the pilot building had an atrium space that required fall protection at every floor. The designed BIM model suggested installing the final guardrail system as soon as the steel had been erected. This could have been achieved by welding the guardrail to the steel in advance before it was hoisted in place. The initially designed solution, however, was not implemented in the field due to a change in the type of the guardrail. The general contractor had to react quickly to this change and implemented a conventional guardrail system during construction which was later replaced by a permanent guardrail system (see Fig. 7i and j)). Another common reason to have a temporary guardrail system in place is to avoid damage to the fixed permanent guardrail during the construction process. In both cases, the rule-checking system can be applied to generate the solution efficiently.

Comparison of manual and automated fall protection model- ing methods

The observed benefits of automated modeling approach are as follows (see Table 1): (1) the time requirement using the automatic modeling method is significantly reduced compared to manual modeling. Usually it takes seconds or minutes to generate the results for a building model as complex as the case study projects.

Higher safety expertise and modeling familiarity is required for manual modeling. The modeler needs to fully understand the model, know how to add and schedule railing components, and more importantly, the modeler needs to be familiar with the safety regulation and requirement. However, the safety expertise is not an essential prerequisite for the automated approach since the knowl- edge has been already stored and programmed in the system. (3) Once a design change or schedule update is made, it is difficult and time-consuming to update corresponding safety requirements manually. On contrary, an automated safety checking system can be easily re-started to generate new results. (4) Manual modeling can provide safety solutions with higher level of detail (see Fig. 8). Before the column and wall can be constructed, the guardrails on the slab edge need to be removed. In Fig. 8(a), the railing posts are carefully positioned closed to the columns, so that no additional posts are needed afterwards. However, automated modeling does not take such detail into consideration. In Fig. 8(b), after the con- struction of the column and wall, one additional post needs to be installed close to the left column. A rule can be created that solves this problem that guardrails extending a pre-specified distance are not possible, and a post must be placed automatically.

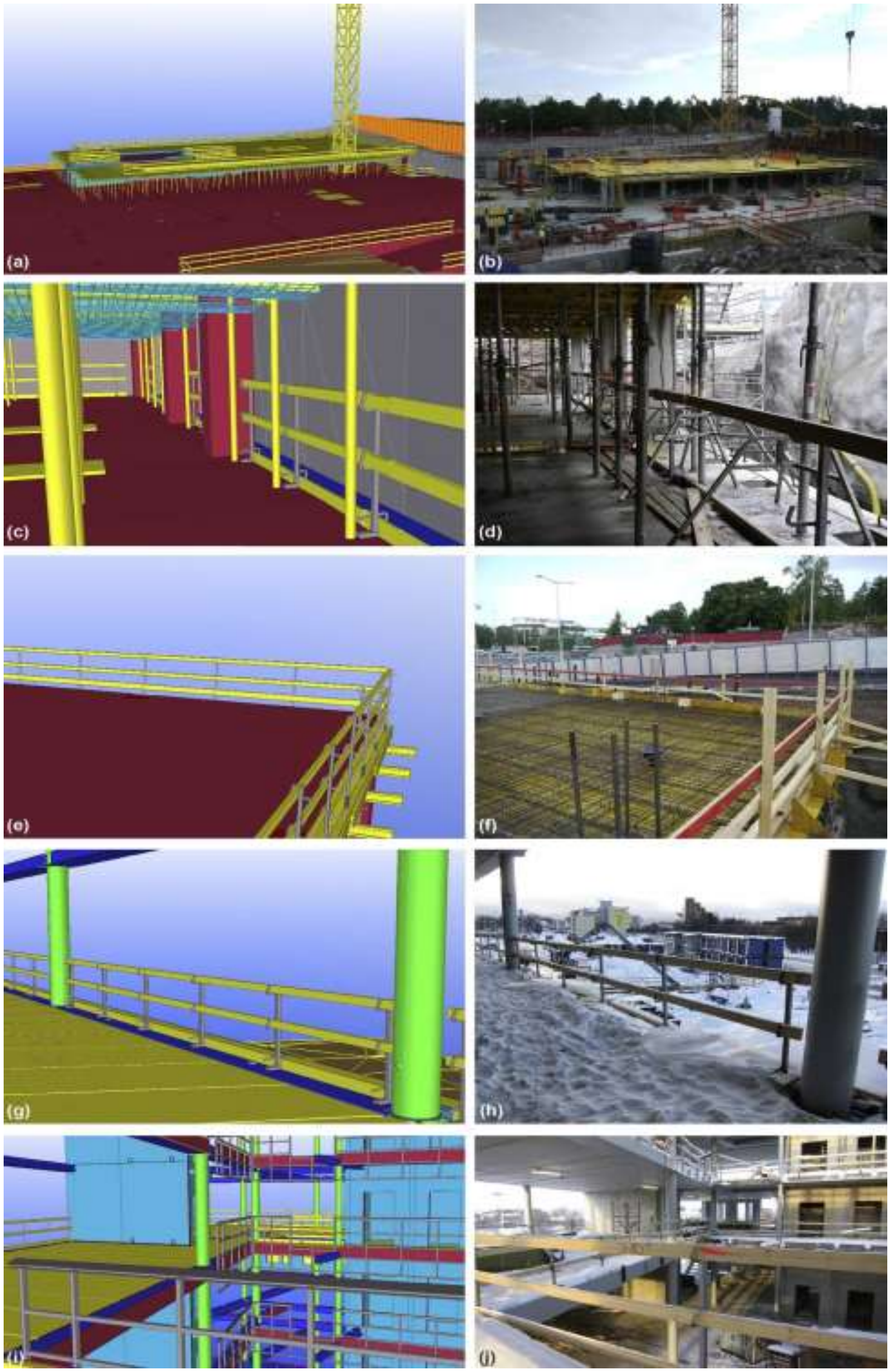


Fig. 7. Comparing model and live situation: (a and b) A general view to the pilot site in basement construction phase, (c and d) at a leading slab edge, (e and f), formwork of a concrete slab, (g and h) safety rail posts are attached with bolts to the welded thread sleeves on the steel beam, and (i and j) General view of temporary fall prevention systems in atrium of
an office building (after Kiviniemi et al., 2011).

Fig. 8. (a) Manual vs. (b) automated modeling results.

Table 1
Comparison of manual and automated modeling approaches.

Manual modeling	Automated modeling	
Time requirement	Long	Short
Required safety knowledge	Very high	Little
Ease of update	Difficult	Easy
Level of detail	High	Low

Case study 2: dynamic fall hazard detection and prevention in BIM

In the second case study, the developed automated rule-check- ing tool was applied on a multi-story precast apartment building model (see Fig. 9). The goal was to demonstrate safety checking results dynamically based on the project schedule. All the precast concrete units were fabricated and transported to the construction site and will be erected with predefined order starting from Sec- tion A, followed by Sections B and C. The façade insulation and brick walls were built on site after the precast concrete stood in place. The project’s structural model had been modeled using Tekla Structures 17.0 modeling software. The 4D schedule needed for the developed automated rule-checking platform was added to the structural model based on information obtained from the contrac- tor. This information was provided by the site engineer in the tra- ditional format of a construction schedule and work breakdown structure (WBS) concerning the installation sequence.

Fig. 10 shows a close view of the concrete slab pieces. The con- nections of the slab pieces are reinforced and cast after the erection of the slabs, while before the erection of the following floor the wall panel erection had already started. Walls and lift shaft together with the slab work as a structural system which transfers the loads to the foundations. The slab sections were erected by

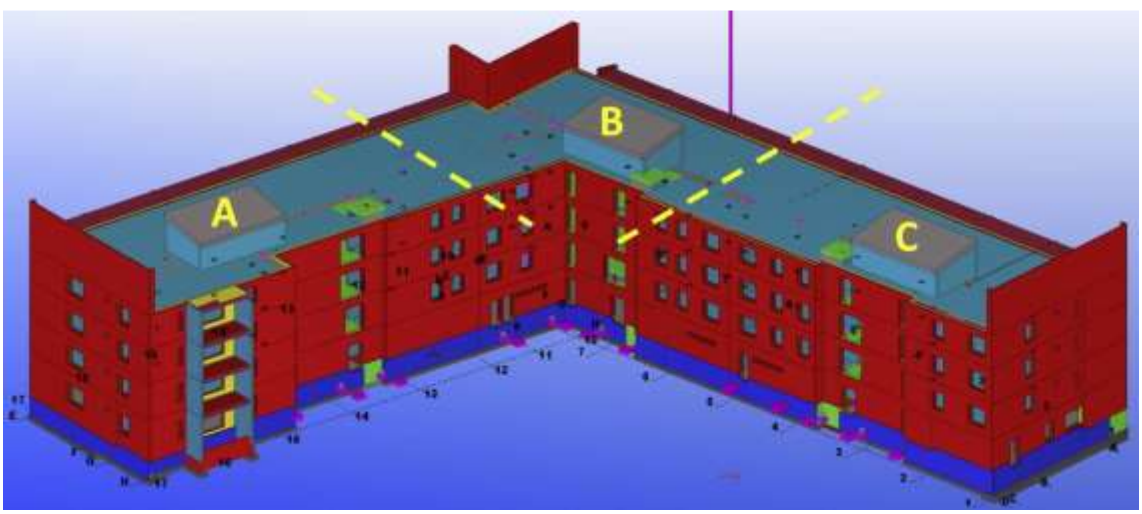
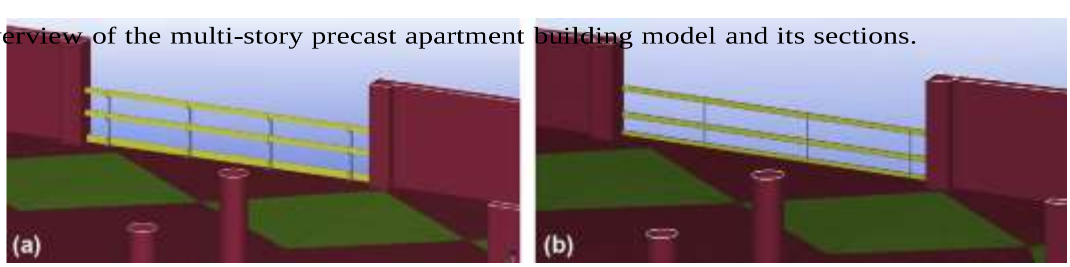


Fig. 9. Overview of the multi-story precast apartment building model and its sections.



story. It takes about seven days to erect one story of a section and about 5–6 weeks to erect one section. The guardrail solutions need to be updated according to the growth of the slab sections. For example, when two slab sections merge on the same level the guardrail in between needed to be removed.

After the rule checking algorithm (Zhang et al., 2013) was exe- cuted, the fall prevention system was executed and visualized in the model automatically, including guardrails. It also created sub- tasks for the installation and removal of safety-relevant equipment into the construction schedule. Fig. 11 shows partially the updated schedule with the required safety solution. Fig. 12 shows the four different phases of the model simulation that are available to provide temporal visualization of the safety equipment embedded into model and construction schedule. The object representation for the 4D simulation is shown in Fig. 13. The slab on the first floor grows from Section A to Section B. Since they merge at some time during construction, the guardrail in between must be removed. Removal also improves the work flow on site, since workers are now able to safely walk from Section A to B without taking any detours. The installation and removal of the building sequence is shown in Fig. 14(a) and (b).

Fig. 14 shows more detailed views of the slab edge protection and wall opening protection. After the generation of the safety pro- tective system in the model, the checking report is also generated automatically. This report can then be exported into a MS Excel format as shown in Fig. 15. Such file formats allow field safety or superintendent simplified use of the generated data. They can, for example, calculate the required safety equipment that is needed to protect the work site. Eventually, the list may also support the pre-fabrication of detailed safety solutions that can be pre-fabricated offsite and installed in similar ways as custom- ized precast concrete panels. Thus the developed tool and the data

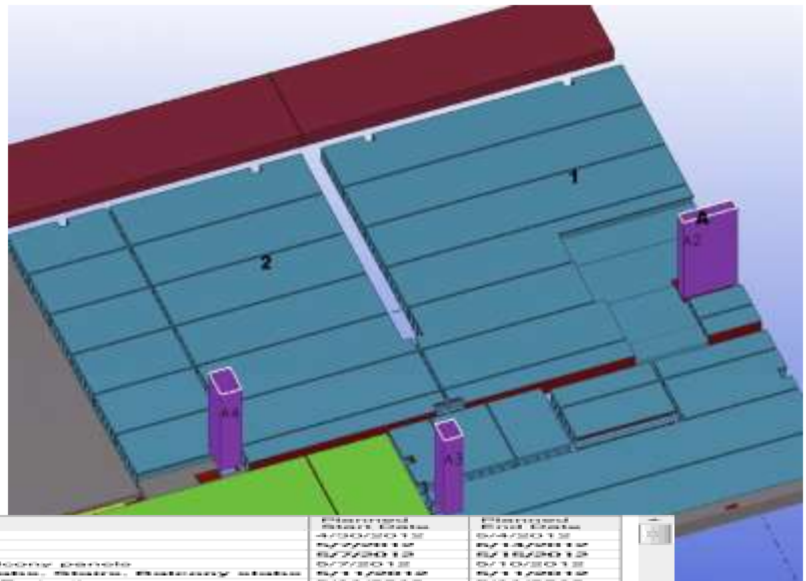
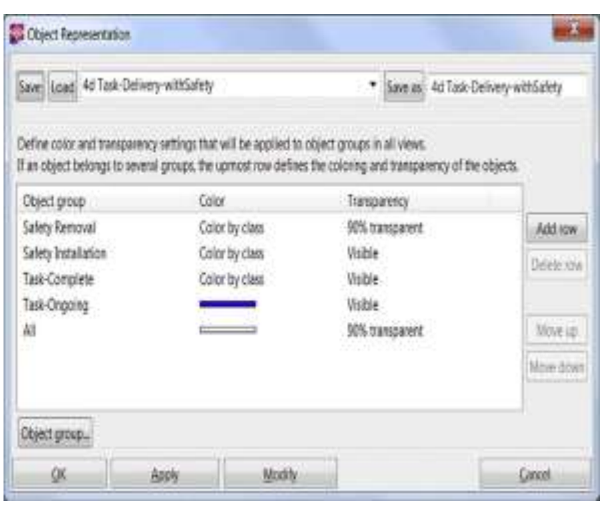


Fig. 10: Close view of precast slab panels.

Discussion

Fig. 11. Updated construction schedule with the installation and removal of fall prevention methods.



it generates support multiple Design-for-Safety (DfS) concepts. Such a list can also be used as an inspection checklist to make sure all the required protective safety systems have been put in place onthe construction site.

The user-interface for slab hole checking is shown in Fig. 16. Users can define their own requirements in terms of different pre- vention methods using the tool's interface. After the rule execu- tion, safety protective equipment will be visualized in the model and also checking results will be listed in a separate dialogue, from which safety manager can preview the results and make changes manually if necessary. This keeps a human decision maker in the loop of protective safety hazard detection and prevention (Zhang et al., 2013).

The developed tool detected unprotected slab edges and installed required guardrail system both automatically and suc- cessfully. Quantity-take-off of the guardrails can be easily calcu- lated using the BIM software's built-in function. In addition, the automated installed guardrail for slab edges and window openings can be modified by a user later manually).

During the test trials, a detailed 3D model for so-called hook posts was successfully integrated in the tool (see Fig. 17). A user is now able to select a simplified model representation or a detailed representation (custom components) for safety railing modeling. In addition, more detailed guardrail models and related safety equipment parts and components, such as welded fittings, could be added and modeled automatically into steel beams or concrete panels for guardrail installation. The corresponding con- nections can be pre-considered in the steel beam or concrete panel fabrication, hence reduce the work at height. However, if a user's goal is to provide detailed and automated safety modeling, a pro- gram needs to be developed much further to improve the rules for post positions as well.

One current limitation of the developed system is that it heavily relies on information provided by BIM such as the geometry and the schedule. If the information in a BIM is incomplete, incorrect, or inaccurate, the correctness of the safety analysis will be largely affected. In addition, building model geometry (e.g., object shapes with complex spatial dependencies) or site conditions (e.g., tempo- rary structures that aid construction processes and are often not modeled) might cause the application of the current version of the rule-checking system to fail, or produce results at best that experienced safety experts would understand and be able to resolve. In order to achieve accurate results, it is recommended to run the automated system to check against the model first. A safety expert would then audit the results and provide his/her input afterwards. Currently, a conceptual fall prevention plan is automatically created using the developed prototype tool by Zhang et al. (2013). An additional area for future research is gener- ation of process flow maps and the role of safety engineers, special- ists, and inspectors as they should take full advantage of BIM- based enabled safety hazard detection prevention planning tools. One first step towards that direction has been made for Automated Job Hazard Analysis (JHA) in the effort by Zhang et al. (in press).

Fig. 12. Object representation setting for 4D simulation.

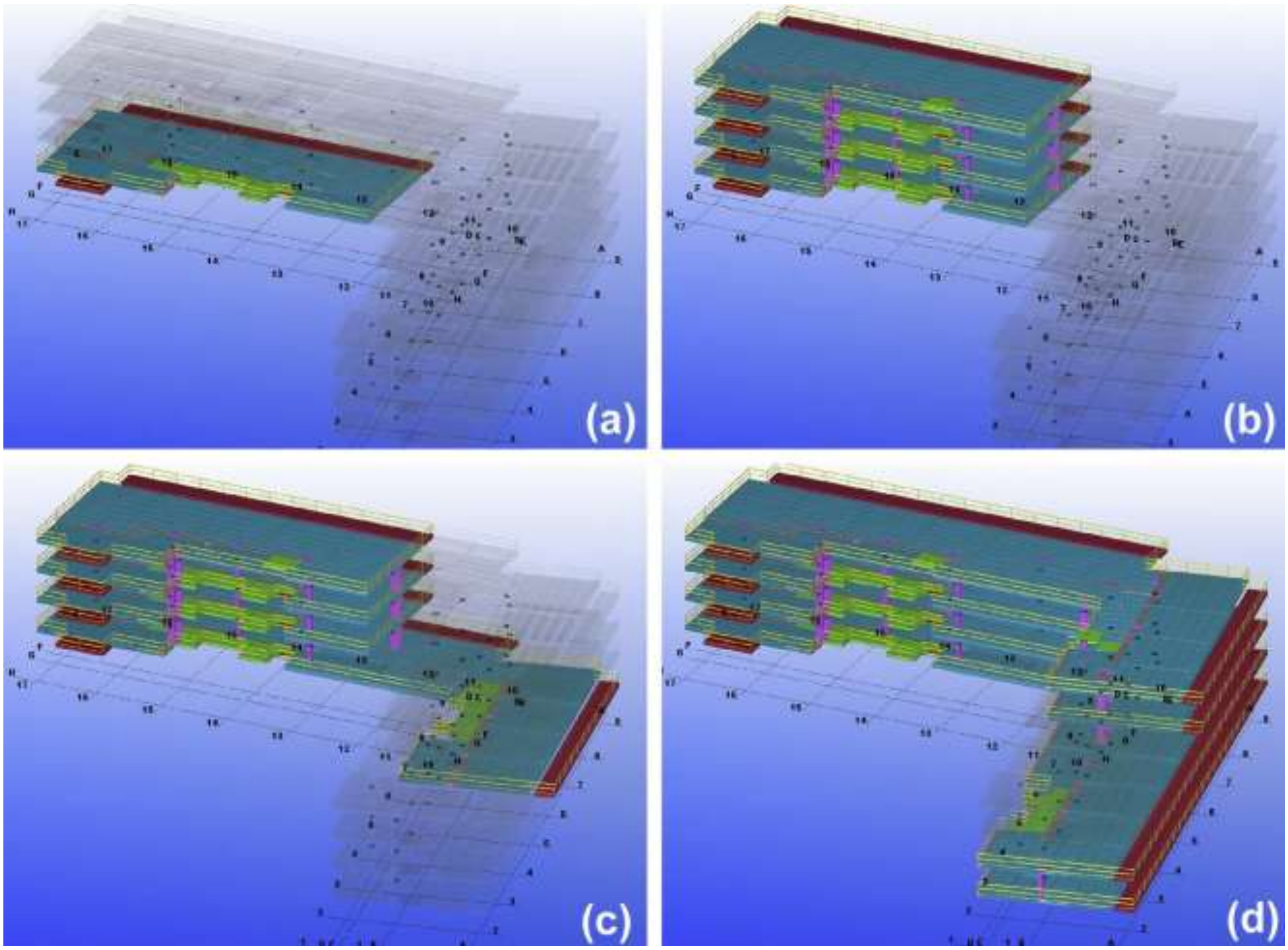
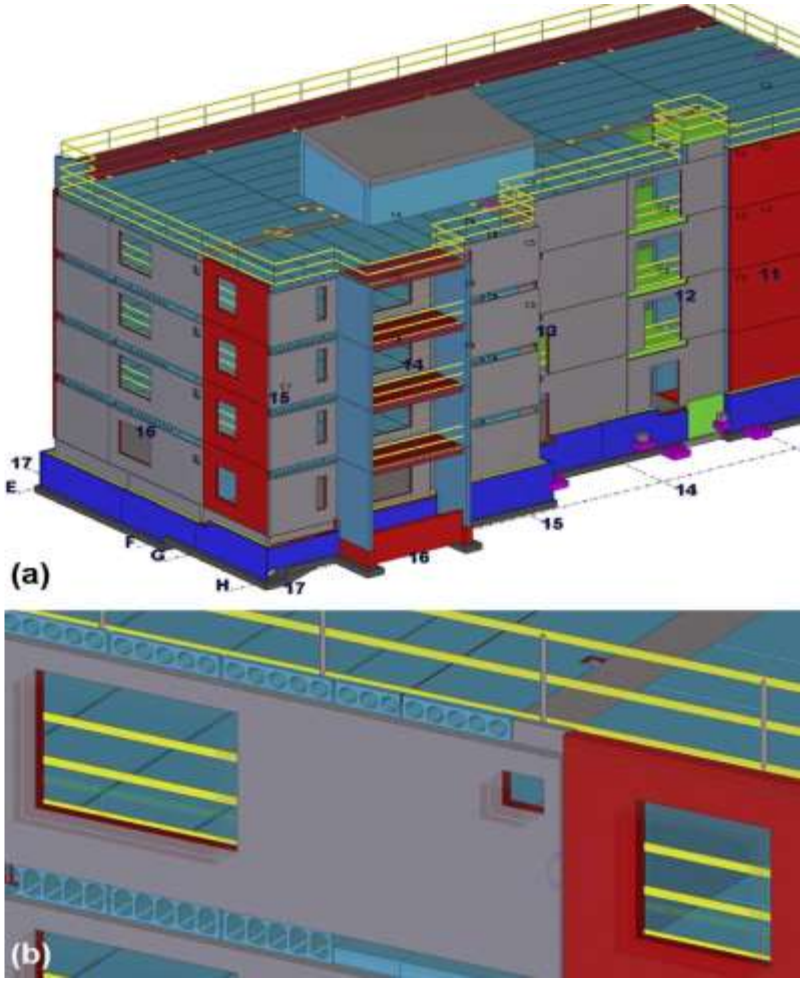


Fig. 13. 4D simulation of the model slab, column, and guardrail prevention systems.

Potential future areas of improvement based on the findings from the conducted test trials are:

Providing high level of the detail to safety elements: Guardrail posts and boards, for example, can be visualized in a BIM with abstract lines. An inexperienced user might prefer high level visual detail of what the posts look like, and in case anchors are needed, which exact location these need to be placed on a concrete surface. An experienced user indeed may be interested in high level of detail for additional func- tionality, for example, when certain safety equipment can be pre-fabricated. Knowledge of complex connections between guardrail posts and building components may accelerate the installation process of such components in the field.



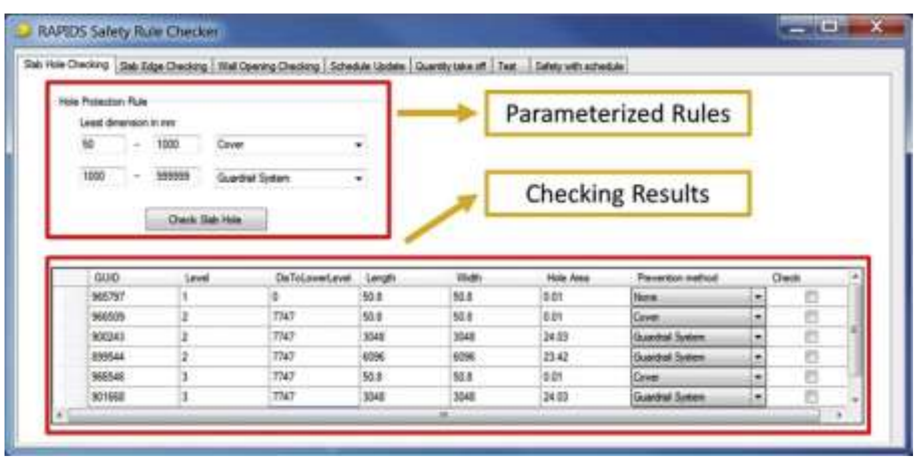


Fig. 14. (a) Protective fall protection systems in Section A of the building and (b) close view of wall opening protection.

Slab Hole Checking Results								
Project Name:			Analyst:			Date: 1/28/2013 2:36:10 PM		
No.	GUID	Level	Distance to Lower Level (mm)	Length (mm)	Width (mm)	Area(m2)	Prevention Method	Check
1	2301919	1	3185	235.86	235.86	0.05	Cover	FALSE
2	1862884	1	3185	110	150	0.02	Cover	FALSE
3	1845126	1	3185	200.01	120	0.05	Cover	FALSE
4	1807649	1	3185	200	200	0.04	Cover	FALSE
5	1808525	1	3185	270	180	0.05	Cover	FALSE
6	1808623	1	3185	200	200	0.04	Cover	FALSE
7	1808591	1	3185	260.91	200	0.05	Cover	FALSE
8	1808719	1	3185	200	200	0.04	Cover	FALSE
9	3390930	1	3185	942.25	614.51	0.09	Cover	FALSE
10	1862931	1	3185	150	110	0.02	Cover	FALSE
11	3390851	1	3185	460	305.03	0.17	Cover	FALSE
12	3390827	1	3185	610	390	0.23	Cover	FALSE

Fig. 15. Bill of materials: slab hole checking results provide an Excel sheet for estimating and prefabrication of safety equipment.

Using software independent data exchange formats: Software independent data exchange formats facilitate easier communication among multiple project stakeholders. An IFC-based solution needs to be explored for safety planning purposes. The ability to use an IFC model for automated safety checking and planning will allow more general checking capability of models created in various BIM model authoring tools.

Testing on complex models: In the future, more comprehensive BIM-based fall prevention planning solutions need to be tested on complex model geometry and provide high level of detail with the entire range of safety solutions. For instance, installing alternative solutions such as safety nets, hooks to tie-back during construction as well as during facility operation and maintenance.

Fig. 16. Slab hole checking user-interfaces.

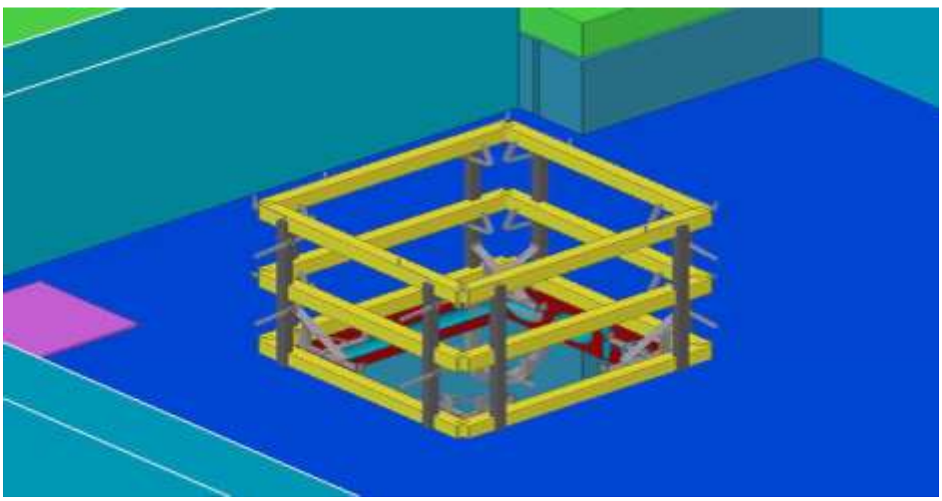


Fig. 17. Realistic and detailed guardrail representation.

both create and modify model items and provide visualization.

Construction site layout modeling and visualization: Recogniz- ing the importance of construction logistics and the dynamic nature of the construction site, it is important to take the construction site layout into consideration for safety. The capability of modeling and visualizing the site layout can support the detailed and accurate analysis of the site logis- tics which then can be used to increase productivity and enhance work site safety.

Model format: As mentioned earlier, the use of IFC data format allows more general checking capability of models created in various BIM authoring tools.

Rule-checking capability: A BIM platform equipped with its own rule engine can provide users the opportunity to self-define or user-configured safety rules for rule-checking process.

Modeling: Construction safety is not only managing or controlling workers' safety behavior; it also involves the design, procurement, installation, and removal of safety and temporary equipment such as guardrails, scaffoldings, and safety nets or hooks. It is essential to also design and model these temporary objects in BIM for visualization and quantification purposes. Thus, an ideal platform needs to be able to

BIM platforms review for supporting safety planning

A number of commercialized BIM platforms were examined for their capability of supporting safety planning. Several functional prerequisites are considered important to enable BIM-based safety planning. They are listed as follows:

Scheduling and simulation: The complex and dynamic nature of the construction industry and its on-site work patterns are widely recognized. In order to detect and prevent safety hazards during the construction process, project schedules need linkage to BIM. In addition, it is critical for the applica- tion to be able to visualize the construction progress accord- ing to the schedule to promote the safety awareness and communication.

The comparison of several existing commercially-available BIM software solutions and their potential for incorporating safety is shown in Table 2.

The strength of using SMC as a BIM-based tool is its capability to use IFC data exchange format, which makes the checking inde- pendent from BIM-based software used for modeling. The rule- checking functionality and user-interface also provide opportunity to incorporate safety solutions (Downey, 2012). However, while automation is used to carry out the routine checking work, some- one still needs to model all safety related temporary equipment and structures, which are not supported or lacking from existing object libraries in BIM-based modeling software. The tedious mod- eling process usually takes days even weeks depending on the scale or the complexity of the project. Similar issue was found with Navisworks, the lack of modeling function makes it difficult to add safety related equipment. The dynamic nature of construction site cannot be shown in either SMC or Revit, which makes it challenging to conduct rule-checking at different construction phases. Since this paper focuses on building-related fall hazards, site layout

modeling and visualization are not the scope of the presented work. Hence, based on the comparative analysis, Tekla Structures® was chosen to function as the implementation platform that incor- porates the safety rule checking algorithms in this study. In addi- tion, a lot of site layout and operation modeling efforts are needed in order to make BIM useable for construction process planning or analysis.

Conclusion

The developed safety rule-checking platform for fall hazard detection and prevention in building information models has been successfully implemented in two case studies. The algorithm was able to detect the location of potential fall hazards in concrete slabs and leading edges, and provides installation guidelines (e.g., bill of materials, visualizations) of corresponding fall protection equip- ment that solve the identified hazards virtually in a BIM. The results show the effectiveness of the proposed approach in detect- ing and visualizing the potential fall hazards in particular during the safety design and planning stages.

Since the automatically generated fall prevention plan must be checked by a safety specialist, it allows adjustment if other safety guidelines or best practices are followed. The developed platform shows strong potential to create BIM-based safety plans, visualize safety in construction schedules, arrange installation and removal work, provide options and procedures including both permanent building parts and temporary safety equipment, and simulate these.

A future goal that might lead to significant change in safety industry best practices is that BIM-based safety planning might become part of the standard building construction planning pro- cess. BIM-based modeling can also increase the safety understand- ing and communication, especially when it is done during engineering design and construction planning phases. Since the construction schedule is linked to the model objects in BIM only a few weeks before the construction starts, it is essential to check the model for changes and update the checking results after a pro- ject's structural model, the schedule, or the original installation order change. The developed system assists human decision mak- ers in this review process by eliminating both the hazards in the design and planning stages, making sure that safety equipment is procured and ready for installation at the right place and time when needed.

When considering benefits of automating BIM-based safety planning instead of carrying out manual modeling, it was found that automation has the potential to advance the BIM-based plan- ning procedure remarkably by reducing time and manual modeling efforts. Once a design change occurs, extra efforts are needed using manual modeling. Time and other human resources are needed to check the model carefully to make sure the modeled guardrail or other protection equipment is still valid and accurate. While man- ual modeling provides the advantage that a human is involved in every step, it is time consuming and potentially error prone. A sys- tem that provides automated and consistent results which are then reviewed by a human can provide more frequent and faster updates.

Current concerns about the application of the developed system include: (1) since model-based designs and construction drawings

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