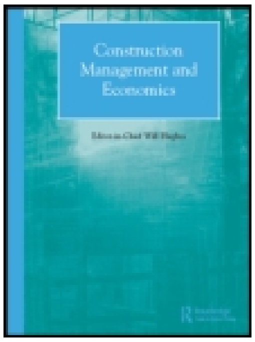

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A case study on automated safety compliance checking to assist fall protection design and planning in building information models

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Worldwide occupational safety statistics show that the construction industry in many countries experiences one of the highest accident rates of all industry sectors. Falls remain a major concern as they contribute to very serious injuries or even fatalities on construction projects around the world. Since the standards and rules for protective safety equipment vary by country, the growing numbers of internationally operating companies are in need of tools that allow ubiquitous understanding and planning of safety regardless of the country where they operate. The problem is examined using a customizable automatic safety rule-checking platform for building information models. The applied rule-based checking algorithms are designed to be add-ons to existing building information modelling (BIM) software and can check models for safety hazards early in the design and planning process. Once hazards have been identified preventative safety equipment can be designed, estimated, and included in the construction schedule before construction starts. A case study implements the safety rule-checking platform on a high-rise building project. Fall protection regulations from both the USA and Germany are applied to the developed rule-checking platform. Visualization of the safety information further explains the differences in the results once country-specific safety-regulative standards are applied on the same building information model. The case study also indicates that the role of BIM in safety design and planning can effectively assist the traditional safety decision-making process for fall protection equipment.

Keywords: Building information modelling, fall protection, prevention through design, safety design and planning, standards.

Introduction

Construction workers are exposed to various dangers in their work environment. Falls from heights are the leading cause of injury in the construction industry. The most common practices to protect workers from falls are applying covers and installing guardrails. Small holes are protected with covers that no one can fall or step into. Leading edges are often protected with guardrails. The rules and standards for fall protection on construction sites are (often) nationally regulated by the country in which the construction work is performed. Based on these requirements, assessment for and installation of fall protection on a construction project is often performed manually and on an as-needs basis.

This paper presents a comparative case study based on an automated rule-based checking system for building information modelling (BIM). The scope of the work focuses on safety rule implementation of fall protection standards from two countries: Germany and the USA. Both sets of safety regulations were implemented and validated on the same case study project. The results show quantitative and qualitative understanding of the applied fall protection standards. A further contribution of this work is the focus on the

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process to embed safety rule-checking into existing safety management practices.

Special attention throughout this paper is paid to highlighting the benefits such a system has on current limitations of users who: (1) may work in multiple countries and require understanding of the differences in safety standards as they apply to each country; (2) request an accurate estimate of the cost of safety equipment before construction starts; and (3) want to understand where, when, what safety equipment is needed to protect workers from hazards in the construction environment.

Background

Accident statistics in Germany and the USA

Construction offers some of the most dangerous work places and historically has one of highest work-related injuries and fatalities rates. Compared to any other industry sectors in the past two decades, the German construction sector reported 55% more frequent accidents (Deutsche Gesetzliche Unfallversicherung, 2010). In Germany, a reportable case is an accident during a job or when commuting which is either fatal or leads to an incapacity to work for more than three days. When relating the accident rate in construction to the amount of full-time employees, construction in Germany has 66.54 reportable accidents based on 1000 full-time workers. Though the accident rates in the German construction industry have decreased in the past two decades, 117 736 reportable work accidents were still witnessed in 2010 (Deutsche Gesetzliche Unfallversicherung, 2011).

In the USA, the construction industry also continues to rank among the most dangerous industries to work for (Hinze and Teizer, 2011). In 2010 alone, there were 751 fatalities from construction work (US Department of Labor, 2011). This number is equal to a fatal work injury rate of 9.5 workers per 100 000 full-time equivalent workers. A comparative statistic of all fatal work injuries in the construction sector in the USA and in Germany for the last five years is shown in Figure 1 (US Department of Labor, 2011).

Construction workers face numerous risks and dangers on a construction project. Falling is one of the most common and often leading causes of fatalities in construction (Derr *et al.*, 2001; Bobick, 2004; Sokas *et al.*, 2009). The statistics of the last five years indicate the persistently high number of deaths and injured workers due to falls. In 2010 264 fall-related fatalities in the USA and 39 fatalities in Germany were reported. According to Bunn *et al.* (2007), falls incurred the highest workers' compensation and hospitalization costs in construction. The average number of absent days for construction workers suffering from falls from heights was 44 days (Gillen *et al.*, 1997). In sum, these statistics indicate that fall-related hazards in construction remain a serious problem.

Many safety and health related organizations, owners and contractors, and many other construction project stakeholders have understood the consequences that are caused by injuries and fatal falls. Their mission since then has been to provide a safe work environment. One goal is to pursue appropriate safety design and planning of fall protection systems that minimize the risk of falling early in the construction planning phase. As many researchers pointed out, awareness of safety during the design phase can improve the safety standard throughout the entire construction phase (Hinze and Wiegand, 1992; Gambatese and Hinze, 1999; Frijters and Swuste, 2008).

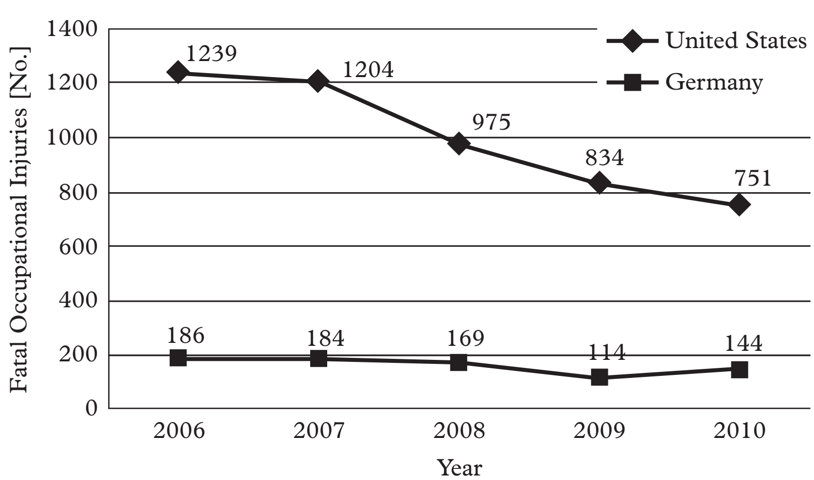

Figure 1 Construction fatalities in the USA and Germany

Research conducted by Huang and Hinze (2003) revealed that inadequate or inappropriate use of fall protection equipment and inoperative safety equipment contributed to more than 30% of fall accidents. Much research has also been done to improve safety in construction by focusing on improvements of safety awareness or technical developments for onsite safety (Garrett and Teizer, 2009). However, it is evident that more attention should be paid to safety as it is used in the early design and planning stages of a project (Qi *et al.*, 2011).

Although building information modelling (BIM) has already been proven as a promising tool to support construction management in the early planning phase (Eastman *et al.*, 2008; Zhang and Hu, 2011), safety yet has to make its impact on BIM. One of the first studies that provided a framework for safety in BIM was by Zhang *et al.* (2011, 2013). The study proposed a safety rule-checking system that applies fall protection such as guardrails and covers automatically to a building information model.

Legal obligations differ by country

The United States' Occupational Safety and Health Administration (OSHA) sets forth minimum guidelines to protect the health and safety of those working in the construction industry and other occupational fields. OSHA's regulation 1926.16 defines that (1) the prime contractor is generally responsible for work site safety; and (2) each subcontractor remains responsible for keeping its workers safe. Dividing up the roles in construction safety can cause problems; for example, a prime contractor that often provides general safety equipment and coordinates the work site safety may not be aware that subcontractors perform work at height on a project. Communication of essential and needed safety equipment can be an issue and often has led to issues on projects.

Germany has a labour protection law that is increasingly internationalized because of required harmonization with European regulations for labour protection. The labour protection law in Germany is based on a dual system. On the one hand, there is a public health and safety law called Staatliches Arbeitsschutzrecht which includes the basic legal obligations of employers and employees. Examples are regulations on recording work hours called Arbeitszeitgesetz, guidelines for workplaces called Arbeitsstättenverordnung, and the general German Occupational Safety and Health Act called Arbeitsschutzgesetz. On the other hand, there are regulations by statutory bodies. Laws are usually supported by a number of regulations or rules of professional associations. They are not as comprehensive as the federal law, but more prescriptive and regulative targeting a certain or specific part in performing a work task. For the German construction industry, mainly the Employers' Liability Insurance Association for Construction (in short 'BG Bau') is responsible for maintaining and controlling safety in the construction industry. The BG Bau publishes regulations to set safety objectives as well as defining industry- and process-specific rules. Such rules include fall protection regulations. These rules are legally binding.

The Regulation on Safety and Health on Construction Sites (called Baustellenverordnung BaustellV) has existed in Germany since 1998 (Verordnung über Sicherheit und Gesundheitsschutz auf Baustellen, 1998). According to §4 BaustellV, the contractor has to provide a safe and healthy work environment. A similar law exists in the USA. This law mandates a health and safety coordinator on German projects where a contractor cannot undertake the tasks himself. Typical reasons for a contractor to hire a safety coordinator are lack of expertise or a small project. The relationship is illustrated in detail in Figure 2.

Although the involvement of a safety and health coordinator adds up to 0.3–1% to the total construction budget, savings can be expected by lowering construction interferences, accident and loss rates/costs, providing better coordination, and sharing of construction equipment (Bargstädt and Steinmetzger, 2010). Furthermore, the involvement of a coordinator on a project does not exempt the contractor from the responsibility for maintaining safe construction sites. The safety and health coordinator according to BaustellV has to actively participate in design and construction planning. Figure 3 shows the responsibilities of the safety and health coordinator during the project development. During the design planning he/she has to elaborate the safety and health plan and communicate the safety and health protection measures with the contractor and planners. Further, he/she has to coordinate the cooperation of the contracting companies in terms of safety and health issues during construction by updating a health and safety plan that must be on the project site during all times of construction.

State of the art in safety planning

Safety planning in the construction industry is complicated due to the dynamic nature of the construction environment and active involvement of various stakeholders. Construction is typically seen as a one-of-a-kind business. Each project is built 'for the first time' and only very few building types are constructed repeatedly. Consequently, construction planning has to start again with the start of a new project. Traditionally, safety planning in construction is separated from

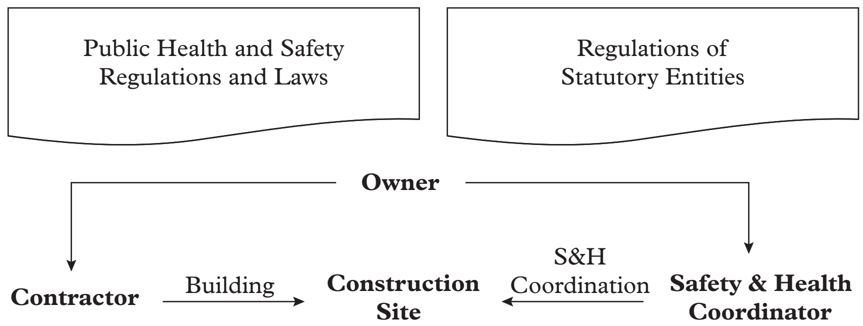

Figure 2 Safety relationship between German regulative entities and contractors

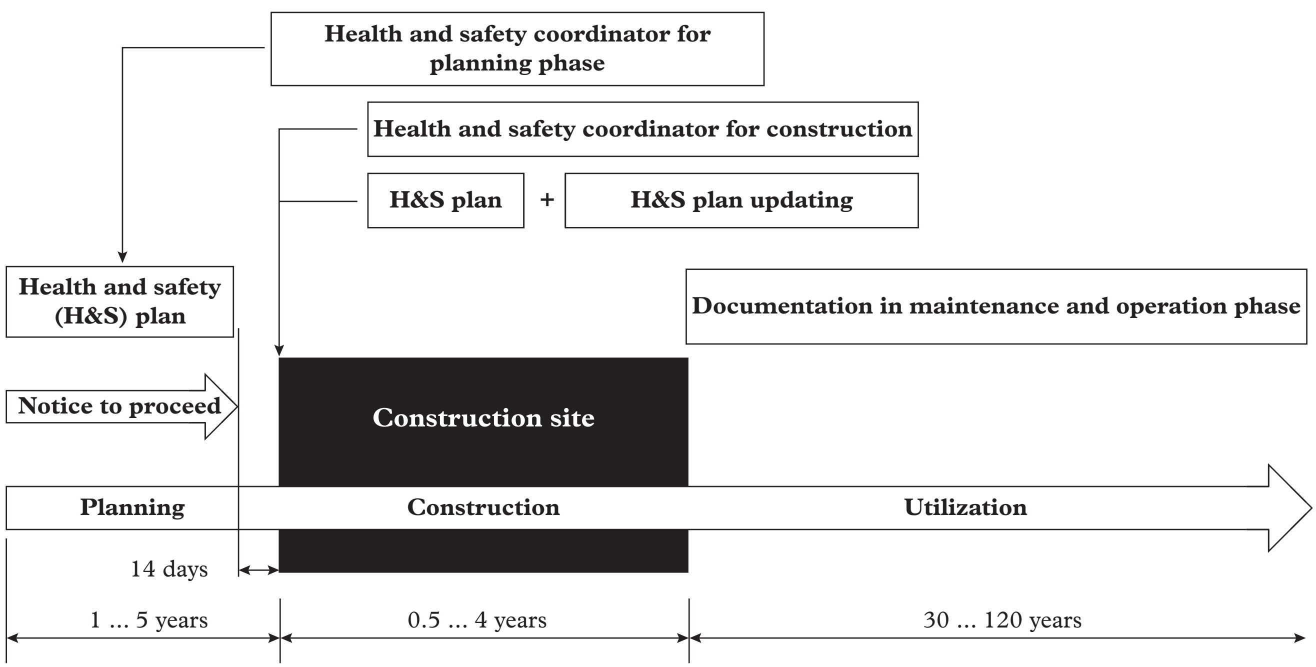

Figure 3 Responsibilities of the safety and health coordinator during the project development

the work planning phase. Frequently experienced issues arise when (1) decisions of the architectural/ engineering design and layout planning team are made without considering safety factors; and (2) the project layout keeps changing throughout the construction phases.

A further well-known characteristic of the construction industry is the fact that there are many project participants. An architect/engineer might well be responsible for the preliminary design and construction documentation. However, the contractor remains responsible for construction site safety (Gambatese *et al.*, 2008). The current state of many construction businesses shows that contractors participate relatively late or very little in the design or planning process. Therefore, the time between contract award until construction start is often too short for detailed safety planning, and any safety planning is deferred to the construction phase. Another often proclaimed problem in construction is the lack of human resources for construction planning as well as for site supervision during the execution phase (Egan, 1998). The introduction of an external health and safety coordinator leads to the active involvement of safety experts in the construction process planning. However, the safety coordinators may not be present at all times on a project, especially if the projects are smaller in size. As a result, responsibilities in safety are delegated to staff or personnel that might not be familiar with the rules and regulations in safety.

Another problem in existing safety planning is the methods to detect potential hazards that put workers at risk or in dangerous work environments. Manual observation and printed (two-dimensional) drawings are only two of the very common traditional practices that exist to interpret existing health and safety hazards. As seen on many projects, safety risk analysis is mostly based on long-time experience of personnel, observation of progress on a site, tasks to be performed, and looking at drawings. Such analysis is often referred to as job hazard analysis (JHA) but is ultimately performed in detail a few days before work is actually performed.

It has been widely acknowledged that safety planning in construction needs improvement. It is in the nature of the construction business though that quality planning and work preparation are directly linked to the knowledge of the executing and experienced personnel. Therefore, knowledge-based decision support tools can help humans to improve the quality of planning. An example is to assist a safety planner or engineer with tools that detect hazards, shifting the focus of the engineer to problem solving rather than problem finding. As an important note, humans should always be involved in the decision-making process, in particular when it comes to safety. Therefore, the proposed framework brings together human experience, best practices, and legal requirements in a knowledge base and applies safety to BIM.

The necessity of an integrated safety planning tool that utilizes the capacity of BIM

As explained before, safety planning can be a tedious and time-consuming task that currently relies on many manual tasks. For large structures, for example a high-rise building, such tasks are repetitive in nature. Floor plans that may look the same can consist of different drawings and the sections that are shown might be in several different building plans (Blickling, 2003). As site conditions also change frequently, it is inadequate to analyse the construction project concerning safety issues only based on information/drawings that represent the final, built status. It, however, is essential to take project schedule into account. All such information is integrated in BIM.

Another often experienced issue in safety hazard detection is the understanding of spatio-temporal relationship of work space and time. Many decision makers yet have to adapt to using the full potential of three-dimensional (3D) and time-based visualization/simulation of information models. Education and training in handling BIM technology for experienced personnel is lacking as a new generation of BIM technology-savvy engineers is growing. Thus it takes the spatial imagination of a safety engineer to study the coherent structure of a building. Such manual hazard analysis is generally a time-consuming and can be an error-prone procedure. Since it is worthwhile to avoid a hazard at the design stage rather than waiting for controlling the hazard or simply protecting the workers during the construction stage (Manuele, 2003), Ku and Mills (2010) discussed in their research the need for design-for-safety tools. One potential solution to fill the gap is to provide (manual) tools that assist a safety engineer in the task of modelling protective safety equipment in BIM (Sulankivi *et al.*, 2010). BIM-based cost estimating, risk management, clash detection and 4D simulation have become established features to support construction management (Hardin, 2009; Eastman *et al.*, 2008; Hartmann *et al.*, 2012). Many other advantages are witnessed by using BIM for project planning.

Xue *et al.* (2012) showed that collaborative work and project management in the architecture, engineering and construction (AEC) industry have substantially grown in the past decade. A review of 83 research papers concluded that industry has finally embraced the advantages of IT-related technologies, such as nD modelling, intelligent agent and virtual collaborative environments. In another study, Hartmann *et al.* (2008) reviewed the success of about 50 case studies in using 3D/4D model applications in the AEC process. Even safety applications in BIM were suggested (Zhou *et al.*, 2012).

Digital building models are widely used in the AEC industries in design and construction. However, further investigation needs to be done for safety planning. Many researchers proclaim that the BIM technology can be used to improve the communication of safety issues (Heesom and Mahdjoubi, 2002; Suermann and Issa, 2007; Eastman *et al.*, 2008). Zhou *et al.* (2012) established a relationship between construction safety and digital design practice. They explored various tools for managing safety in construction, such as databases, virtual reality (VR), geographic information systems (GIS), sensing technologies, and BIM. Researchers at the VTT Technical Research Center of Finland developed a BIM-based safety management and communication system (Sulankivi *et al.*, 2010). They proposed 4D-BIM as a central technology for construction site safety planning (Merivirta and Mäkelä 2011). Benjaoran and Bhokha (2010) developed rule-based algorithms for the automatic identification of hazards when working at height and provided proper safety measures. Qi *et al.* (2011) developed a tool to check model elements based on predefined safety rule sets. A user needs to manually select a specific rule set which will be checked against the building model. Another existing approach to combine safety planning and virtual environments is 4D-CAD-Safety. It assists a safety engineer to analyse and to utilize a safety plan (Chantawit *et al.*, 2005). The user has to manually assign the 3D-model, schedule, and safety measurements.

The limitations of current applications in safety using BIM for safe design and planning of construction work can be summarized as follows: (1) hazards are manually detected; (2) software can semi-automatically fit safety equipment to the identified hazards in BIM; (3) hazards and prevention methods can be visualized in 3D and communicated to all project stakeholders and levels; and (4) work space conflicts can be visualized in 4D (3D plus schedule).

Framework for automated safety rule-checking platform

The rule-checking framework

This work focuses on implementing an automated fall hazard detection and protection platform based on object-oriented building information models. By integrating safe design early in a construction project, hazards can be identified, quantified, and prevented.

The early process of rule-checking in BIM has been introduced by Eastman *et al.* (2009). In early studies, building models were checked for compliance with fire codes and the Americans with Disabilities Act (ADA). The proposed safety rule-checking framework for fall protection was developed in the RAPIDS Construction Safety and Technology Laboratory in the School of Civil and Environmental Engineering at the Georgia Institute of Technology. Details of the rule-based safety checking framework and algorithms that will be applied in this case study are explained in Zhang *et al.* (2013). The safety rule-checking framework that is applied follows five major steps (see also an illustration in Figure 4):

(1) Safety standards and regulation which are commonly described in textual format need to be interpreted in a machine-readable format. Rules also have to link with building objects. For instance, safety rules for fall protection for work at great height must link to existing leading edges of slabs in the building information model.
(2) Reliable and error-free automated safety rule-checking requires that the object-orientated model fulfils strict design requirements. Each building object must have information such as name, type, attributes, relationships, and some metadata.
(3) The rule execution is the connection between the interpreted rule base and the prepared building model. The building objects will be linked to the rule sets by name, type, or other attributes. The rule execution is designed to have two steps: (a) automatically check the model and apply safety measures according to default settings; and (b) provide additional solutions which a user can select should it follow more closely an individual best practice or, among other good reasons, be more cost-efficient. The latter requires additional contextual rule sets.
(4) The results of the rule execution approach can be reported in two different formats: (a) the applied safety equipment can be visualized in the 3D model for visual inspection; and (b) a table-based report shows detailed information about what solution is applied in every single case a hazard was detected. In the latter case, a bill of material quantifies how much safety equipment is needed. Linking such information to the construction schedule allows 4D simulation of safety equipment.
(5) The proposed framework is a decision support system and does not replace the experience of a safety engineer. However, decision experience and making can be improved through the provision of information as explained above.

Fall protection rules (holes, slab edges, openings)

The proposed framework contains three rules to detect the geometry of fall hazards. Only the first two are applied in later sections of this paper as we demonstrate automated fall protection for slabs (not walls) only.

Rule 1: A hole in a slab is defined in OSHA's rule 1910.23(a) (Occupational Safety and Health Administration, 2012). According to the standard, every stairway, ladder way, and hatchway floor opening shall be guarded by a railing to prevent persons from falling. According to OSHA a hole in a slab is defined as a gap or void of two inches (5.1 cm) or more in its least dimension. Holes should be covered if an opening measures less than one metre but more than five centimetres in its least dimension. Holes with a default value measuring greater than 1.5 metres will be protected with a guardrail system.

According to the German occupational safety regulations for safety and health at work, all openings in floors, ceilings, roofs, etc. have to be protected to ensure the health and safety of workers from falling (BGV C22 §12a). In this standard openings are defined as:

- holes with a surface less than or equal to 9 m; or
- straight-line openings where one edge is less than or equal to 3 m long.

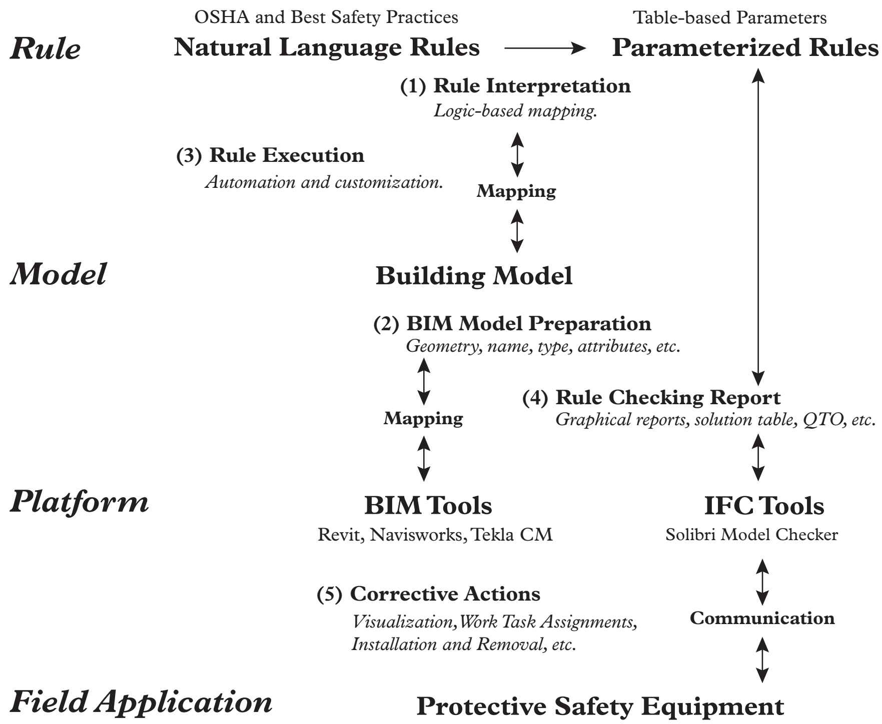

Figure 4 Rule-checking process for rule-based safety checking system (Zhang *et al.*, 2013)

The safety requirements are fulfilled when the holes or openings are guarded or covered with walkable and in-displaceable cover plates. The safety rules according to the two standards (USA and Germany) are represented in table-based format (see Table 1).

Rule 2—Slab edges. According to OSHA, all employees who are working near a leading edge that is elevated equal to or more than 1.8 metres above the next lower floor, shall be protected by guardrail systems, safety net systems, or personal fall arrest systems (§1926.501(b)(1)). The equivalent German rule is BGV C22 §12 (as explained in rule 3).

Rule 3—Holes in exterior walls. According to OSHA §1926.501(b)(14), ‘each employee working on, at, above, or near wall openings where the outside bottom edge of the wall opening is 6 feet 1.80 m or more above lower levels and the inside bottom edge of the wall opening is less than 1.00 m above the working surface, shall be protected from falling by guardrail system’. The equivalent German rule is BGV C22 §12. Fall protection devices have to be applied to prevent a person from falling when the drop height is more than 1.00 m on wall openings. The converted rules in table-based format are shown in Table 2.

The developed algorithm for fall protection is structured in the following way. First, the attribute type ‘slab’ or ‘roof’ will detect the related building objects that carry such names. The rule-checker acquires the geometrical attributes of the object type. If there is a hole in the slab, for example, the algorithm will apply the first rule. In a parallel step, all exterior walls on the slab are identified that have openings. If there is no exterior wall, potentially unprotected (leading) edges will be identified and rule 2 will be applied. Once the rules have been applied, the results are visualized in the building model to allow a user to review the applied fall protection in the virtual world.

Table 1 Rule interpretation for the example of a hole in a slab

OSHA rule		German rule	
< 0.05 m	No action required*		
0.05 m < x < 1 m	Apply cover	< 3 m	Apply cover
Otherwise	Apply guardrail system	Otherwise	Apply guardrail system

Note: * according to safety code.

Table 2 Rule interpretation—hole in an exterior wall

OSHA rule		German rule	
Drop height < 1.8 m	No action required*	Drop height < 1 m	No action required*
Drop height > 1.8 m	Apply guardrail system	Drop height > 1 m	Apply guardrail system

Note: * according to safety code.

Quantity estimates and integration of fall protection system mobilization and demobilization into the construction schedule also become available.

Fall protection systems

Existing methods

Fall hazards on construction sites can lead to fatalities or serious injuries. Therefore it is necessary to provide the appropriate protection systems. In determining the most suitable protective measures, collective protective systems have priority over personal protection measures. Safety equipment which can protect several workers in general has preference over measures which can only protect a single worker. In general, fall protection systems have to be selected according to the following criteria:

(1) Collective fall protection: includes guard railings, covers, or side protection which fulfils the requirements of a collective protection method.
(2) Absorption of present forces: construction processes are very complex and manifold. In some cases, for example confined spaces, construction may not permit a standard fall protection system. Equivalent methods must be installed to absorb the worker(s) when falling. Such alternative methods can be security nets which are able to absorb the forces that originate from falling workers or objects.
(3) Individual hazard protection: the final method that should be taken into account is the individual protection from hazards. If the first two criteria do not provide the appropriate protection, an individual fall protection system has to be designed and applied. Before applying any individual fall protection, such as a personal fall arrest system, a risk assessment for any such case is required.

Types of protective safety equipment

Fall protection devices are used in various construction application areas. The rule-based checking systems utilize two of the most common fall protection methods:

(1) *Cover for holes*: Hole covers offer effective and simple solutions to protect workers from falling or stepping into holes. They also protect workers from falling objects, such as debris or tools, which fall through the holes. According to OSHA 1926.502(i), covers shall support at least twice the maximum load of the largest traffic load.
(2) *Guardrail system*: Guardrail systems can also protect workers from falling. It depends on the safety regulation what criteria guardrails have to fulfil. To show the difference in international standards only the design of the top rail of a guardrail system is discussed further: according to German safety rules, the top rails must be located at a height of 1.00 m plus/minus 0.05 m. The US equivalent rule states the height of the top rails must be 1.10 m plus/minus 0.08 m above the working level. Since guardrails usually consist of a top rail, a mid rail and a toe board, the differences in German and US guardrails are illustrated in Figure 5.

Case study

Implementation of the automated safety rule-checker for fall protection

The fall protection safety rule-checking system was developed as a plug-in to existing BIM software. It is able to check geometric attributes directly in Industry Foundation Classes (IFC)-based BIM (Zhang *et al.*, 2013). An object-oriented 3D building model of a high-rise building project was selected for the case study. Since the model was not IFC-based, the model was exported to an IFC-based model. The safety rule-checking system was then applied to check the model for all fall protection hazards and potential mitigation strategies.

Project description

Since the research by Hatipkarasulu (2010) emphasized that most of the fatalities relating to falls occur on residential and commercial projects, the immediate application of the safety rule-checker to a high-rise commercial building project provided enough reason

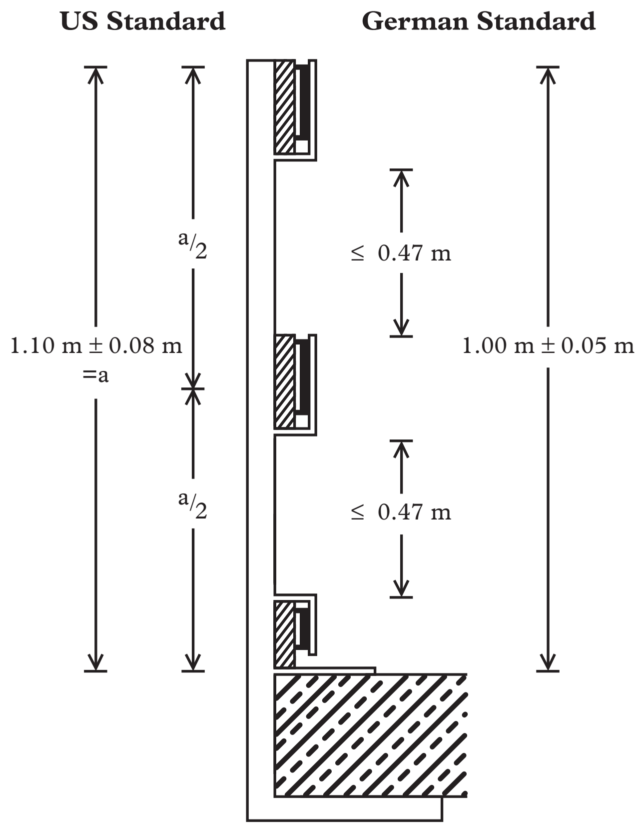

Figure 5 Safety parameters applied to a guardrail protective system

to test and research the benefits and limitations of the developed rule-checking system. The available building information model for the case study is an 87 m tall reinforced concrete building. The gross floor area of the building is about 75 000 m. The model represents the structure of the building including different types of openings in slabs as well as polygonal and rectangular slab edges. The initial rule-checking focused on the identifying and modelling of the required fall protection equipment at 18 standard floors which exist in the model of the high-rise building.

As mentioned before, the case study focused only on the first and the second fall protection rules (holes in slabs and leading edges). By applying the safety rule-checker developed by Zhang *et al.* (2013), the building model was first checked using OSHA's regulations. Thereafter, the same rule-checker and model were evaluated using the German safety regulations. Type of required safety equipment and quantity take-off show how the differing safety rules influence construction safety management on the same project. Furthermore, the changes in workflow management due to the automated planning approach can be provided based on the results the safety rule-checking system provides. In a hypothetical case where the same building would be constructed in both countries, all project stakeholder and in particular construction (safety) managers could easily understand and convey safety information and eventually point out differences to staff and workers more easily.

Results

The following paragraphs describe qualitative and quantitative benefits and current limitations of the developed automated safety rule-checking system for fall protection as it was applied to a high-rise building project.

Advancement of workflow management

Various reasons exist for the increasing importance of workflow management. The need for lean construction, knowledge-based representation of employees' know-how, and computer-aided project development are just a few arguments for investing more in the detailed awareness of workflows in construction management (König, 2006). As the rate and complexity of business processes in construction companies are growing steadily, information has to be available at the right time and at the right place. Furthermore, members of the involved project team (s) may act spatially separated from each other. Therefore the distribution of actual information is the key for a successful workflow. A BIM-based project development can fulfil the conditions of fragmented planning tasks. Automated safety planning with the presented rule-checking system can very much change the future in safe work planning. The integration of the applied system into the safety planning workflow has been shown in Zhang *et al.* (2013). Safety data in construction projects can further be used, updated, and exchanged multiple times and among many stakeholders. An integrated information system can minimize the effort of construction safety planning and at the same time improve the safety standard by collecting and analysing safety data that could not be measured before a safety rule-checker was used (e.g. quantities of required safety protective equipment). Although the developed safety rule-checker is still novel in research and initial use, the ease of updating safe design and plans requires relatively little effort compared to design modifications that traditionally require vast expenditures of time and consume a lot of personnel's experience.

Estimating, managing, and controlling change orders in design and construction planning processes

Traditionally, architects and structural engineers create 2D drawings without much consideration of the potential consequences that safety requirements have during the construction phase. During the tender phase, the general contractor typically estimates the cost and quantity of required safety equipment using in-situ observations and manual reviews of drawing packages. Frequently occurring change orders lead to revision of drawings and then require adjustments in design, cost, and schedule. Once design is complete, a safety engineer will review the drawings again during the work preparation phase. He or she will analyse the construction plans for safety hazards, and finally decide what prevention method must be applied. Finally, the construction site foreman, who is responsible for the installation of the guardrails, covers, etc., estimates the required material for the upcoming work week and orders approximated quantities of safety equipment. In reality, the effort of planning safety is lagging reality. In many cases, the ordered amount of safety equipment depends more on packaging, its unit size and on the available loading capacity of the truck that delivers it.

The developed technology can improve the existing processes in at least three ways: (1) based on the design model, the safety engineer applies the rule-checking system and makes necessary design modifications by visualizing the potential hazards; and (2) the bill of quantities is generated automatically; and (3) the generated report can support the foreman for ordering the correct type and amount of safety equipment which is delivered just in time.

Time savings

Another big advantage of the automated safety rule-checking system is time savings. Manual observation and drawing reviews require large amounts of time, are labour-intensive, and consequently cost more money than planning for safety with human-assisted tools. In general, BIM-based safety planning delivers detailed reports and visuals in less than a few minutes (in the presented case study).

Accuracy of results and material forecasting

Optimized material storage is often a key factor in a successful construction project. Schedule and cost pressures demand accurate estimates and just-in-time delivery. Safety planning in BIM enables accurate estimates and needs of safety equipment on at least a weekly timescale. An automated safety planning tool can also assist human decision-making and reduce the risk of arithmetic or other human errors in estimating.

Bill of quantities and quantification of risks

Neither schedule nor accurate cost calculation can be prepared without a detailed bill of quantities. Although some software providers try to reduce the risk of estimating quantities by using model-based quantity take-offs, these systems are mostly limited topermanent structures and bulk materials in construction. Temporary facilities, including safety preventive equipment, are normally not considered in drawings or modelled in 3D building models. The developed method thus reduces the risk of forgetting safety positions and specifications for tenders by automatic determination of all the relevant components.

Equipment and material used in building construction depend often on national laws, regulations, rules, and standards that are hard for non-experts to comprehend. For increasingly international construction projects and their workforce, it is becoming important that planning tools exist that easily adapt to changes in rules and can also be easily understood by a user. The following analysis demonstrates the impact that country-specific regulations and rules have on the construction safety planning process.

Quantity take-off of safety equipment

The quantity take-off of the automated safety rule-checking system reports in detail where, when, what, and how much equipment is required for fall protection. Figure 6 shows a detailed view of the results of the safety rule-checker as it detected the hazards and automatically applied guardrail systems and covers for the holes and leading edges. The guardrail systems and covers which resolve all identified and located fall-related safety hazards are illustrated in Figure 6 with three parallel lines and a black cover, respectively. The differences in results between applying the US and German safety standards have been visualized in Figures 6a and 6b. The US safety standard resulted in applying much more guardrail system while the German safety standard applied more covers for the same hazard location.

Holes in slabs

Falling through a hole in a slab can cause serious injuries and even fatalities. The automated safety rule-checking engine first automatically detects all holes in the slab (see Table 3) and then proposes two prevention methods. Table 3 shows an extraction of the report that resulted from the detection of all slab

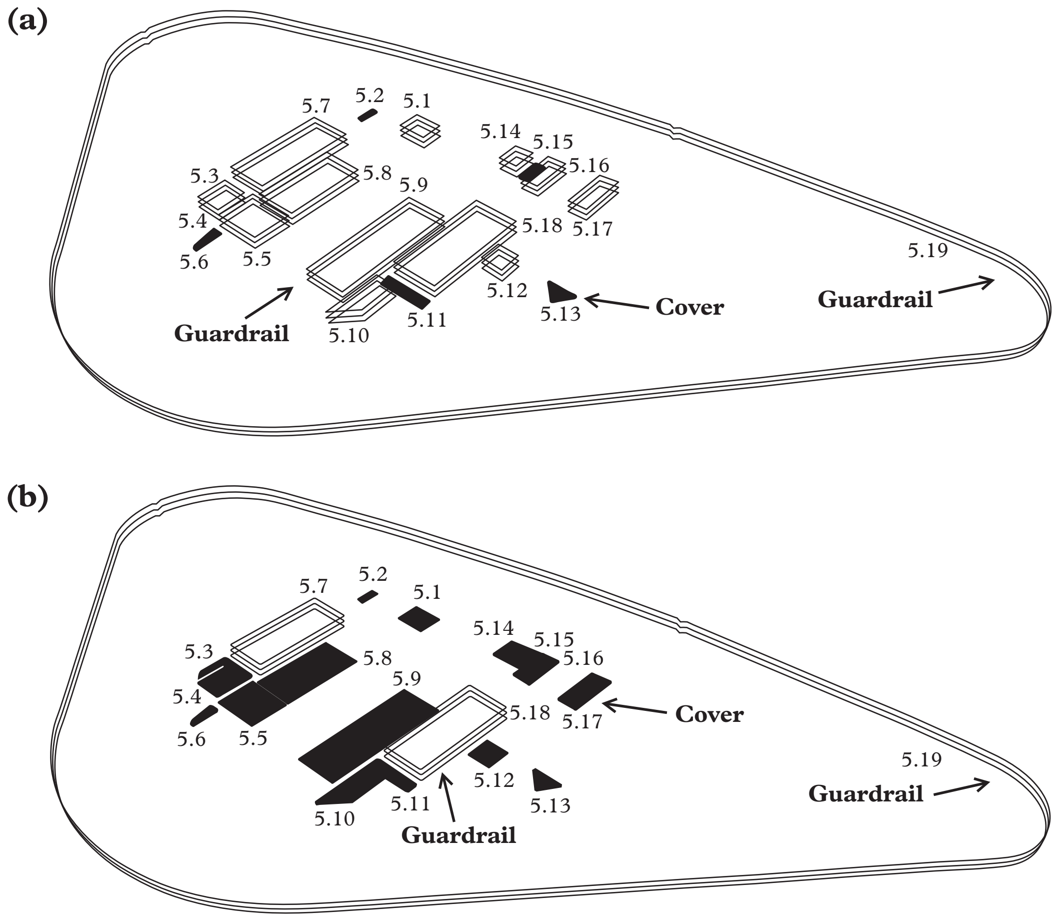

Figure 6 Isometric view of the protective safety systems (guardrail systems and covers) the safety rule-checker proposed for the leading edges and holes on the concrete slab of the fifth floor according to (a) OSHA guidelines and (b) German safety standard

Table 3 Extraction of the fall detection report for holes in the slab on the fifth building floor

Floor no.		Floor area		Area of all openings	
5		1369.85 m^2		121.98 m^2	
Hole no.[Floor.Hole]	Area(m^2)	Width(m)	Length(m)	US standard	German standard
5.1	3.46	2.16	1.60	Guardrail system	Cover
5.2	0.55	1.42	0.39	Cover	Cover
5.3	1.20	1.96	0.62	Cover	Cover
5.4	3.91	2.06	1.90	Guardrail system	Cover
5.5	8.16	3.25	2.51	Guardrail system	Cover
5.6	0.92	1.79	0.52	Cover	Cover
5.7	21.32	6.88	3.10	Guardrail system	Guardrail system
…	…	…	…	…	…

openings on the fifth building floor. The calculated floor area is 1369.85 m^2 and the total area of all openings is 121.98 m^2. All of the detected openings were consecutively numbered and their properties were listed. For example, opening number 5.1 has an area of 3.46 m^2, width of 2.1 m, and length of 1.6 m. The table further shows the proposed prevention method based on *a priori* known rule sets.

Table 4 Detected hazardous objects on each floor according to predefined rules

	German standard		US standard	
	Qty	Dimension	Qty	Dimension
Holes	17	79.35 m^2	7	8.44 m^2
Openings	2	39.92 m	12	144.21 m

The total number of detected hazardous objects (holes and floor openings) is listed in Table 4. Every floor in the building model has 17 holes according to the German standards and 7 holes according to US standards, respectively. After German regulations, the total area for covers is 79.35 m^2 (about 10 times the size of covers that OSHA suggests using). These data potentially affect the construction schedule, as covers can or cannot be more quickly installed than guardrails. Before installing any protective system, it can even be accurately measured and safely prefabricated outside busy construction areas.

Unprotected slab edges

The report for preventive equipment generated by the safety rule-checker indicates the need of guardrails for a total of 157.89 m of unprotected slab edges per each floor (see Figure 6). The safety rule-checker reporting system provides further information, such as the distance to the lower level and the number and type of protective equipment pieces required for installation. By choosing a certain type of guardrail, safety personnel can estimate the exact amount of material for each floor (see Table 5).

Visualization of results

One major issue for proactive safety planning is the detection or identification of potential safety hazards. It has been recognized that virtual learning environments can help to improve occupational safety education and training efforts. 3D and 4D building models can provide realistic visuals of the construction environment and function as valuable aids in the safety decision-making process. With the proposed method, safety engineers can then detect and assess safety hazards and finally evaluate the most appropriate and cost-efficient safety method. They could also explain to work crews where hazards exist and how appropriate safety equipment needs to be installed or what it should look like in the field. The example in Figure 6 illustrates how easy it is to communicate fall hazards to project participants and workforce.

Table 5 Quantity take-off for guardrail system for the seventh floor

Floor No. 7	Length: 157.89 m	
Quantity	Type	Dimension
79 pieces	Post (steel)	100 cm
316 m	Railbord (wood)	3 cm × 15 cm × 200 cm
158 m	Toeboard (wood)	3 cm × 10 cm × 200 cm

Limitations and discussion

The applied automated safety rule-checking framework can improve the workflow and quality of safety planning. However, there are some current limitations and challenges.

When applying the framework to existing safety regulations, it requires effort to analyse and convert text-based safety regulations to a table-based machine-readable format. This can be time-consuming if done manually, but would be required only once. Any future change in safety regulations could occur immediately in the machine-readable format. Changes in safety codes, however, hardly happen frequently.

The design phase in construction is characterized by many changes, and in particular these affect the geometry of building elements (objects). Almost every modification of the building model can affect the outcome of the safety rule-checking system. First, not all safety rules that exist in best practices, rules, or regulations could be checked using the proposed safety rule-checking framework. Many rules require the experience of humans or their nature cannot be explained by applying geometric calculations. Secondly, the system would need to be restarted by the safety or planning engineer whenever the model, objects, or their attributes are changed. The rule-checking process may also be more a dynamic process which is executed more frequently or whenever a change occurs to a model.

Furthermore, a building information model may represent information on a static building element only without taking the construction sequence into consideration. However, buildings are erected in many different construction stages (e.g. concrete pours require joints between them). Additional hazards for the workers may arise from such construction sequencing.

Although other limitations exist, many of them that relate to geometric problems can ultimately be solved. Safety rule-checking in BIM, whether automated, human-assisted, or manual, may find its greatest limitation when accounting for qualitative safety hazards, e.g., safety behaviour.

Future research needs were identified: (1) improve the integration of construction safety and BIM early in the design and construction planning phases; (2) explore the range and possibility of checking other than fall construction hazards; (3) integrate the IFC schedule with the model to simulate and visualize potential safety hazards and protective equipment dynamically; and (4) extend the existing IFC schema to include construction safety related entities, relationships, and properties for facilitating the transfer of building properties stored in the design model to a construction management tool.

Conclusion

This paper introduced an advanced design and planning approach for construction safety. It detects potential fall hazards using the IFC design model and also recommends safety protective equipment based on predefined rule sets. The rule sets are both customizable and extendable. The customizability of the rule sets addresses the different safety codes, regulations, standards, and best practices which can exist on international construction projects. Fall protection rules from both Germany and the USA have been applied in a case study of a high-rise building model. Aside from visualizing the fall protection equipment in BIM the developed rule-checking system was able to automatically generate quantity take-off and installation and removal schedule information of the guardrail system and hole covers. Such information can effectively help a construction manager and/or superintendent to visually understand the potential hazard and plan for prevention. In addition, rather than estimating the needed safety protective equipment, the generated accurate quantity information can help to achieve optimized safety material ordering and storage on the construction site. Taking advantage of BIM technology, the presented approach has the potential to assist the existing construction safety planning workflow and enhance the understanding of safety at the project front-end design and construction planning stages.

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