BIM-based fall hazard identification and assessment in construction projects

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Abstract

The construction sites face significant safety challenges, particularly related to fall hazards and mainly due to the improper placement or handling of protective equipment. As a result, the number and severity of occupational accidents in the construction sector remains unacceptably high globally. This study aims to address this problem by investigating how such potential fall hazards can be identified early in the project planning phase and use this information to more effectively manage the hazards in project execution phase. The methodology employs Building Information Modeling (BIM) technology to dynamically model the construction site and work characteristics in relation to safety matters. Through this process, visual risk representation, labelling, and assessment are developed in places with height-related safety risks. The proposed methodology introduces an automated rule-checking tool that integrates safety considerations into the BIM plan. This integration enables construction participants to promptly identify, evaluate, and proactively react to fall-related hazards, thus minimizing the number and impact of accidents in construction sites. The effectiveness of the proposed system has been validated through several case studies, demonstrating its practical implications for the industry. This study contributes to advancing safety planning and design processes and leveraging information technology to enhance proactive safety management, improve decision support, and ultimately create safer working environments.

Keywords
Risk management, construction safety, fall hazard identification and assessment, Building Information Modeling (BIM), pattern recognition.

1. Introduction

Construction is one of the most unsafe industries, accounting on average for 36% of the fatal occupational-related accidents in the last ten years. This is partly due to the harsh and hazardous work conditions but also to the inexistence or improper placement of protective equipment. Among several accident types, fall from height hazards are among the leading fatality causes in the construction industry. Most lethal accidents in Greece are associated with falling from height, accounting for 40% of all accidents (HAS, 2017). According to the Center for Construction Research and Training (CPWR), fatal injuries caused by falls in U.S.A. (in period 2003-2015) are falls from slabs and roofs (31%), from ladders (24%), and from scaffoldings and work surfaces (15%) (CCRT, 2018). Despite the increasing attention that is given to safety management in recent years, the fall accident rates in the construction industry remain noticeably high. Risks are gradually growing due to the increasing structural complexity, project size, and the adoption of new and complex construction methods (Shim *et al.*, 2012, Zhou *et al.*, 2015). Therefore, fall hazard analysis has been a key target research and development for safety intervention and accident prevention in construction.

Construction safety management can be defined as a systematic and comprehensive process for handling safety risk, which aims at providing a safe and healthy occupational environment, while preventing work-related injuries and sickness (ISO 45001, 2018). Safety management needs to be considered at all construction stages including the preconstruction, the construction, and project operation and maintenance. In pre-construction stage (design and planning), potential safety hazards are identified and decisions on proper safety measures are made, based on the experience of the safety officer and the project manager, as described in the project Safety and Health Plan (SHP).

During the construction stage, concerns about health and safety become of paramount importance, as a result of existing uncertainties and unforeseen circumstances. In fact, the risks in the field generally deviate from the identified ones during project planning and design and this should be considered in developing the safety and health plans (e.g., make provisions for unexpected events or situations based on previous experience in similar circumstances). Finally, during the project operation phase, the accident risk is mainly encountered in maintenance works.

Several digital tools that can assist work planning have evolved in recent years, which can enhance the ability to deal with safety issues in construction. Among them, Building Information Modeling (BIM) is a digital representation of physical and functional characteristics of a facility. The application of BIM is rapidly increasing nowadays in construction process planning and management as well as in safety management. A starting point for efficient safety management is through emphasizing safety aspects early in structure design and engineering phases (Zhou *et al.*, 2012).

This research outlines a framework for fall hazard area identification and risk evaluation, employing a rule-based control system to assess whether the appropriate safety measures are fully and properly implemented in the construction site according to safety standards. The proposed method integrates BIM software for developing digital images of the project site, both for the ideal and actual conditions in terms of safety measures, and an algorithm that compares these two images for automatically identifying any possible absence or misalignment of the safety measures. Following, the risk level is assessed for each hazardous area considering a number of risk-related attributes and valued according to the actual safety conditions in situ.

2. Background

The Architecture, Engineering and Construction (AEC) industry has witnessed a rapid development all around the world, especially in developing countries and during the last few decades. Large-scale projects have become widespread and international, new project delivery methods and techniques are being adopted, design theory and tools are constantly improving, creative and new approaches, methods, and materials of construction are being introduced (Bryde *et al.*, 2013). Emerging technologies including database, computer-aided simulation and visualization provide new opportunities to enhance safety planning (Eastman *et al.*, 2011). Information and Communication Technologies (ICT), such as Building Information Modeling (BIM), have become established tools in AEC. BIM and BIM-related technologies are considered useful tools to overcome the existing obstacles in traditional risk management methods. For instance, BIM can be considered as a potentially effective way to assist early risk identification and assessment for design and construction through 3D visualization (Grilo and Goncalves, 2017). BIM has been rapidly recognized to improve the process of construction project delivery. It has been also realized that BIM can be employed to promote safety management and combine safety with other construction planning processes.

One of the promising directions of BIM applications in the AEC industry is to facilitate several rule-checking processes and simulations for evaluating different aspects of design and planning in the early phases of a project. A BIM platform can also function as a tool for providing easily accessible and understandable visualization of up-to-date progress on construction and safety over time and, in particular, for detecting hazardous spots and conditions in the construction area. Further, the automatic generation of safety measure proposals can assist safety managers planning upfront and developing safety plans before construction commences. This includes planning safer work tasks and monitoring the planned work during construction.

There are several research methods that focus on Job Hazard Area (JHA) identification during design and planning phase with computer-assisted and BIM-related technologies. Getuli *et al*. (2017) have presented an H&S BIM-based design and validation workflow, specifying the minimum level of requirements and mandatory informative content for the development of construction site layout and safety plans, analyzing construction phases, and identifying potential safety issues in a virtual environment. The Rule-based Code Checking on the design phase, comparing Building Information Models against current codes, legislation and regulations, was translated into parametric rules of corrective actions. In order to predict and evaluate falling risk, Chen and Luo (2016) have employed three types of data mining methods (decision-tree learning algorithm, artificial neural network, and clustering algorithm) to analyze the Occupational Safety and Health Administration (OSHA) data. Fifteen OSHA recorded parameters are considered for investigating their influence on the injury severity level. Through the importance analysis of the parameters and comparison of the three data mining algorithms, the features for proactive fall injury protection in construction sites have been analyzed. Hongling *et al*. (2016) have proposed a method for comparing the safety rules and the building information stored in BIM. The safety rule system is built on categorizing safety rules and then extracting basic and necessary information from them. Each rule is attached to a unique code while each component is matched with a unique component code, which represents its properties and parameters. Components information is extracted from

BIM and each component is paired with safety rules by matching component ID and safety rule ID. By comparing component parameters and related information in safety rules, unsafe design factors are identified, visualized in BIM, and rectified. Zhang *et al.*, (2014) have investigated how potential fall hazards, which are unknowingly built into the construction schedule, can be identified and eliminated early in the planning phase with a framework that includes automated safety rule-checking algorithms for BIM methods. The work has presented two case studies which refer to (a) comparison of manual and automated fall protection modelling and (b) dynamic fall hazard detection and prevention in BIM. Zhang *et al.*, (2016) have developed an approach of integrating BIM and expert systems (B-RIES), which is composed of three main built-in subsystems (BIM extraction, knowledge base management, and risk identification) and aimed at providing real-time support for decision making to address deficiencies in traditional safety risk identification process in tunnel construction. Navon and Kolton (2007) have developed an automated model to monitor, and control fall hazard. The model algorithms are designed to follow up the existing guardrails and constantly compare their locations and lengths to the planned ones, during construction and design stages. The model input comprises five datasets concerning risk factors, activity characteristics, safety regulations, general project data, edge identification & marking. The guardrail's actual location is detected by sensors. The graphical outputs present a 2D floor plan of the project, from AutoCAD program, which depicts the dangerous areas. Kim *et al.* (2016) have introduced a safety planning platform, implemented in BIM, to simulate and visualize spatial movements of work crews using scaffolding. Computational algorithms have been developed to identify temporary structure-related safety hazards automatically during the construction simulation. However, some limitations of the method were recognized, in particular (a) the current path creation mechanism requires a user to manually specify crew work paths and (b) the hazard identification focuses solely on supported scaffolds used by masonry crews.

The examined research efforts typically focus on a single part of the safety management, either risk identification or risk assessment. The present study aims to implement an integrated methodology for identification and evaluation of risks associated with worker falls from height in construction sites. In such a direction, early warning may be provided and appropriate preventive or corrective actions may be planned, to minimize risks and prevent accidents or casualties.

3. Methodology

The proposed methodology implements a BIM-based automated tool which provides decision support in identifying and assessing potential fall hazards in a construction project. During construction, several types of fall hazard spots may be encountered. They include leading slab edges, slab holes, wall openings, ground holes, stairways, portable ladders, scaffoldings, excavations, wells, elevated work floors, construction machinery, lifting equipment, etc. In such cases, protective equipment (such as fall protection barriers, fencing, guard railings, etc.) plays a key role in preventing accidents or reducing their probability or impact. The lack, misplacement, or temporal removal of such equipment could highly result in the exposure of the workers to (fatal) accidents. In this work, the research effort is directed to the identification of such inappropriate placement and handling of protective equipment and the assessment of the potential consequences of such omission.

3. 1 Risk identification

A BIM platform allows architects/engineers/designers to check a project during the design process by using a design-modeling tool. With such a tool, designers can easily validate their model at each construction phase, in accordance with the safety rules, thus avoiding making extensive design modifications while construction work is in progress. The proposed development aims to collect and analyze construction data, in the form of 3D images of the construction site, developed during the design phase through the structure and site BIM model at different construction instances. The images are directed to fall hazard work areas and aim to capture the existence and proper placement of protective equipment. Two sets of images (the designed one representing the ideal safety protection plan and the actual ones representing the real work environment over time) are exported from the BIM tool (in particular, Autodesk Revit) as a ".png" file type to Matlab for identification and evaluation of potential risks. In this part of the methodology the designed (original) and actual (current) image are compared to identify possible deviations and assess the potential risk level of these deviations (Tsoukalis and Chassiakos, 2019).

3.2 Risk evaluation and assessment

Following identification, risk assessment is the second key element of safety management and provides the means for analyzing and evaluating the risk level at each location and circumstances. This assessment can assist decisions regarding risk treatment and appropriate preventative measures to be put in place, as well as evaluate the degree that these measures are satisfactory (BSI, 2021). There are different approaches for risk assessment; the one that is conventionally used includes two main parameters, the likelihood (probability) of an adverse event or situation occurrence and the expected consequence (impact or loss) resulting from the actual appearance of the event or situation. Therefore, estimates of the two parameters are required in order to evaluate the risk level and to decide mitigation strategies that can reduce the risk probability and/or severity.

For the risk assessment of falling from height, a set of attributes are being proposed in this study considering available accident data and expert judgement. The attributes, which are related to the likelihood of occurrence and the anticipated accident impact, are presented in Tables 1 and 2 respectively.

Table 1. Fall hazard attributes concerning likelihood of occurrence

Likelihood attributes	Explanation	Score value based on condition
Side protective equipment	Existence within specifications (minimum height from the floor, intermediate bar protection) and quality of side fall protection equipment	1: equipment existence in good condition and height > 1m 2-4: partial existence, moderate condition, height < 1m 5: equipment inexistence
Working floor condition	Existence within specifications (minimum width 60 cm), consolidation, operationality, quality/level of damage of working floors in height	1: good quality - consolidation, width > 60 cm 2-3: middle omissions, quality &-consolidation, width < 60 cm 4-5: serious omissions, bad quality - consolidation, width < 30 cm
Gaps	Gap between the working floor and the lateral fall protection equipment or wall within specifications (less than 30 cm)	1: gap < 30 cm 2-4: gap 30 cm - 60 cm 5: gap > 60 cm or not protective equipment at all
Mounting - fastening	Quality, condition of mounting - fastening of working equipment (ladders, scaffoldings etc.) to safeguard stability	1: high equipment stability 2-4: moderate equipment stability 5: poor equipment stability
Distance from drop point	Worker distance from fall edge	1: distance > 3 m 2-3: 0.6 m < distance < 3 m 4: 0.3 m < distance <0.6 m 5: distance < 0.3 m
Supervision	Systematic supervision of project activity execution	1: very sufficient 2-4: moderately sufficient 5: inefficient
Organization - planning	Organizational and planning level for performing construction work	1: very sufficient 2-4: moderately sufficient 5: inefficient
Skill - training	Training and experience level of workers	1: very sufficient 2-4: moderately sufficient 5: inefficient
Winds	Wind speed that may affect worker stability	1: low wind speed 2-4: moderate speed 5: high speed, strong winds

Table 2. Fall hazard attributes concerning accident impact

Impact attributes	Explanation	Score value based on condition
Fall height	Height from start to end of fall	1: height < 0.75 m 2: 0.75 m < height < 1.5 m 3-4: 1.5 m < height < 3 m 5: height > 3 m
Body posture	Position of the worker's body before and during the fall	1: good body posture 2-4: moderate body posture 5: bad body posture
Use of holding equipment	Use of worker holding equipment during the fall (restraint belt, safety net)	1: equipment existence and in good condition 2-4: partial existence, moderate condition 5: equipment inexistence

4. Case study

The present case study focuses on excavation works in a construction site. The typical 3D view of the site, developed in Autodesk Revit and exported as "png" file type for further processing, is shown in Fig. 1. The depth of the excavation is about 3.5 meters. In order to protect workers from falling, legislation requires installation of protective equipment at the edges around the excavation. The protective equipment should be durable and fall protection barriers or guardrails (from wood or metal) with one meter height from the ground and intermediate bar at height 0.5 m. A portable ladder is further used for letting workers go up and down the excavation. According to safety practice, the ladder needs to extend at least one meter above the ground level.

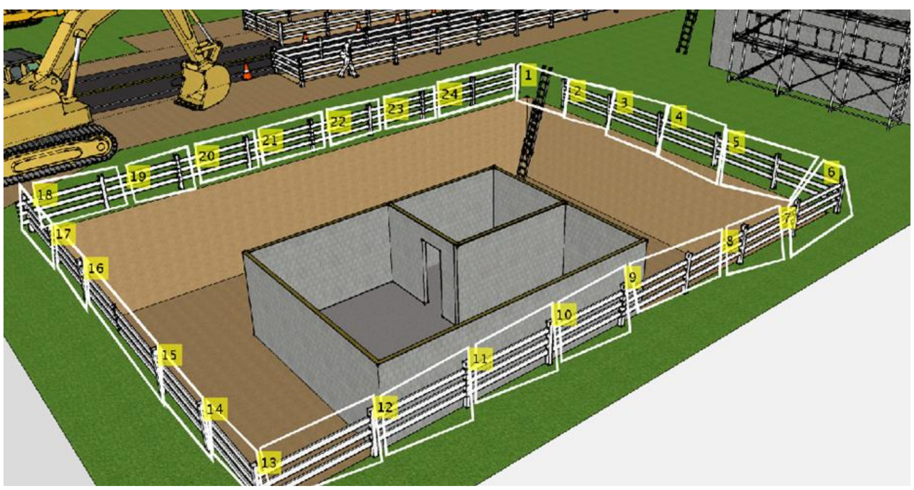

Fig. 1. View of the construction site with the defined check areas

It has been observed that, in such projects, warning signs, fencing, guardrails or safety fall barriers are not typically placed in accordance with the safety standards or are removed or relocated to the side to make work easier. However, this takes place at the expense of increased accident occurrence likelihood. To avoid or reduce such hazardous circumstances, the proposed methodology is used for automatically detecting the lack or misplacement of safety fall barriers or guardrails in specific fall hazard areas around of the excavation. To do so, the fall hazard area is fragmented, with each piece being marked with white frames and numbered, as shown in Fig. 1. The image with the accompanied information is introduced to Matlab, representing the ideal safety conditions, and makes up the baseline for comparison with actual images during project implementation.

As images from project execution become available, they are inserted to the model and compared to the ideal ones (Fig. 2). Further, for each of the identified fall hazards areas, the risk assessment parameters are calculated. The calculations include the scoring criteria values from Tables 1 and 2 for likelihood and impact attributes respectively. Further clarification of the main fall characteristic values of Tables 1 and 2 is provided below in relation to the potentially unsafe areas all around the excavation of Figure 2.

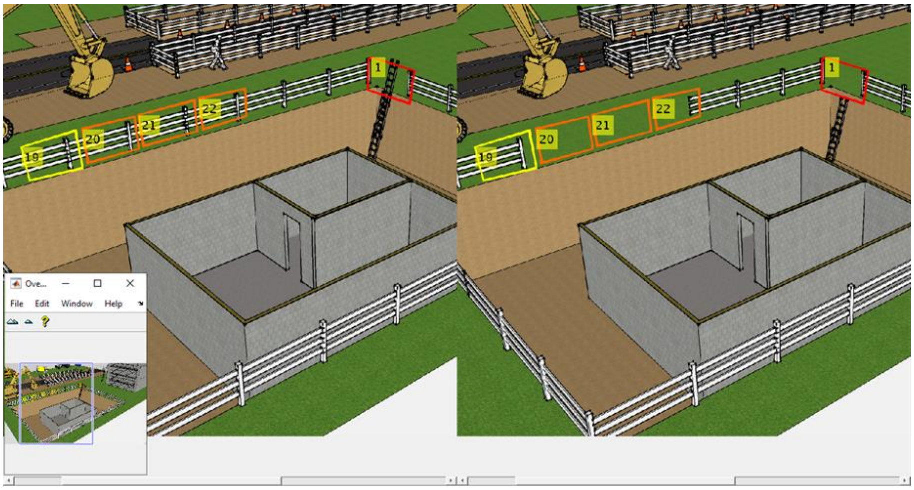

Fig. 2. Original and current site images with the identified fall hazards areas

<u>Area 1:</u>

There is a portable ladder with its top edge just reaching the ground level. The safety rules impose that the ladder top should extend at least one meter above ground level for the safety of workers going up and down the ladder and for providing a side protective equipment for workers approaching the ladder. An indicative fall hazard assessment is presented below, with reference to Table 1 and 2 provisions.

- Side protective equipment: case 5 (fall protection barriers missing).
- Working floor: case 4 (ground edge, steping down the ladder).
- Gap: case 5 (the gap from ground edge > 60 cm, side protective equipment not present).
- Mounding - fastening: case 5 (the ladder is not sufficiently fastened for safeguard stability).
- Distance from drop point: case 5 (workers using the ladder are close to the excavation edge).
- Body posture: case 4 (poor worker's body posture at the start of descent or end of climbing up the ladder due to insufficient ladder height).

<u>Area 19:</u>

- Side protective equipment: case 2 (fall protection barriers partially missing).
- Working floor: case 3 (ground edge).
- Gap: case 2 (small gap from ground edge, fall protection barriers partially missing).
- Mounding - fastening: case 2 (fall protection barriers partially missing).
- Distance from drop point: case 1 (personnel working outside the excavation in safe distance from the drop point).
- Body posture: case 2 (moderate worker's body posture).

<u>Areas 20 and 21:</u>

- Side protective equipment: case 5 (fall protection barriers missing).
- Working floors: case 3 (ground edge).
- Gap: case 5 (gap from ground edge > 60 cm, fall protection barriers missing).
- Mounding - fastening: case 5 (fall protection barriers missing).
- Distance from drop point: case 1 (personnel working outside the excavation in safe distance from the drop point).
- Body posture: case 2 (moderate worker's body posture).

Area 22:

- Side protective equipment: case 3 (fall protection barriers higly missing).
- Working floors: case 3 (ground edge).
- Gap: case 3 (moderate gap from ground edge, fall protection barriers higly missing).
- Mounding - fastening: case 3 (fall protection barriers higly missing).
- Distance from drop point: case 1 (personnel working outside the excavation in safe distance from the drop point).
- Body posture: case 2 (moderate worker's body posture).

Following the above considerations, the resulted risk assessment parameters for the five checked areas are presented in the result report of Table 3. Area 1 presents the highest exposure (21.09) associated with a high likelihood and impact of fall from height. In this case, prompt remedial action (using a ladder of appropriate height) should be taken to ensure acceptable work safety conditions. On the other hand, the risk exposure in area 19 is rather moderate (9.75), which means that a safety measure (placing the fall protection equipment properly) is needed but at a lower priority than the previous case.

Table 3. Risk assessment for identified fall hazards areas

Hazard area	Hazard type	Likelihood index	Impact index	Risk exposure index
1	Fall from height	4.44	4.75	21.09
19	Fall from height	2.31	4.24	9.79
20 & 21	Fall from height	3.83	4.24	16.24
22	Fall from height	2.82	4.24	11.96

The proposed methodology and tools can assist safety managers in terms of identifying hazardous conditions on-site, assessing the risk level, and making prompt decisions for hazard prevention or mitigation. A limitation of the developed method is that risk identification is based on hazard-free conditions obtained by BIM simulation. As such, the identification of hazards in real-life may not be as effective since the actual practice rarely coincides with the simulated one, while environmental conditions (e.g., light level, weather conditions, object interference) may obscure the relevance between the two instances. The same process of comparing risk-free and risk-present images can be achieved with actual pictures from the construction site, provided that a hazard-free work environment has been established at some point in time so that the corresponding picture is taken and used as the basis of comparison. The external condition interference issues still hold in this case and may be considered as a subject of future work. Another future research direction is the consideration of other types of hazardous conditions, e.g., accidents with machinery use.

5. Conclusions

The construction process comprises several and dissimilar phases in terms of work operations and safety risks. It is a dynamic process in which the construction activities change continuously according to project design, planning and execution. The Safety and Health Plan (SHP) and safety construction drawings are employed to support safe working conditions during construction. In real practice though, inefficiencies of such means in predicting and assessing fall hazards in a highly deviating construction environment are observed. Advancing, thus, the safety planning and design process can provide a vital opportunity to mitigate hazards before they appear on-site. Information technology can potentially play a key role in reducing accident/fatality rates considering that it positively influences several aspects of current construction management practices.

This research outlines a framework for fall hazard area identification and risk evaluation employing a rule-based control system to assess whether the appropriate safety measures are fully and properly implemented in the construction site according to safety standards. Risks are mainly associated with the absence or improper placement of warning signs, fences, protective equipment, scaffoldings, excavations, slab edges, portable ladders, holes, construction machinery etc., which could play a role in work accidents and injuries/fatalities. The proposed method integrates BIM software for developing digital images of the project site, both for the ideal and actual conditions, in terms of safety measures, and an algorithm that compares these two images for automatically identifying any possible absence or misalignment of the safety measures. A Matlab code is used to deploy the hazard identification algorithm at several predetermined check areas. If differences between the original (ideal) and current (actual) safety measure placement are detected, the type and the spot of the potential risk are indicated by displaying the two images side by side, with hazard areas clearly highlighted.

Following, the risk level is assessed for each hazardous area considering several risk-related attributes and valued according to the actual safety conditions in situ. The resulting risk assessment table with risk parameter (likelihood, impact, exposure) evaluation for each identified fall hazard area serves as the means to prioritize hazardous spots and to plan corrective actions to minimize the risks. In fact, prompt safety alerts are raised and communicated to the safety or site manager, specifying the point and type of nonconformity to the designed safety measures. The proposed model has been tested in a number of case studies and appears to be a valuable tool for prompt and effective restoration of safety measures, preventing thus accidents and reducing the possibility of undesired consequences to project execution.

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