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A review of risk management through BIM and BIM-related technologies

Yang Zou^{a,*}, Arto Kiviniemi^b, Stephen W. Jones^a^a School of Engineering, University of Liverpool, Brownlow Hill, Liverpool L69 3GH, UK^b School of Architecture, University of Liverpool, Leverhulme Building, Liverpool L69 7ZN, UK

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ABSTRACT

Risk management in the AEC (Architecture, Engineering and Construction) industry is a global issue. Failure to adequately manage risks may not only lead to difficulties in meeting project objectives but also influence land-use planning and urban spatial design in the future growth of cities. Due to the rapid development and adoption of BIM (Building Information Modelling) and BIM-related digital technologies, the use of these technologies for risk management has become a growing research trend leading to a demand for a thorough review of the state-of-the-art of these developments. This paper presents a summary of traditional risk management, and a comprehensive and extensive review of published literature concerning the latest efforts of managing risk using technologies, such as BIM, automatic rule checking, knowledge based systems, reactive and proactive IT (information technology)-based safety systems. The findings show that BIM could not only be utilised to support the project development process as a systematic risk management tool, but it could also serve as a core data generator and platform to allow other BIM-based tools to perform further risk analysis. Most of the current efforts have concentrated on investigating technical developments, and the management of construction personnel safety has been the main interest so far. Because of existing technical limitations and the lack of “human factor” testing, BIM-based risk management has not been commonly used in real environments. In order to overcome this gap, future research is proposed that should: (1) have a multi-disciplinary system-thinking, (2) investigate implementation methods and processes, (3) integrate traditional risk management with new technologies, and (4) support the development process.

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1. Introduction

The AEC (Architecture, Engineering and Construction) industry has witnessed a rapid development all around the world, especially in developing countries, during the last few decades – large-scale projects have become widespread and international, new project delivery methodologies 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). AEC projects such as buildings, infrastructure systems and plants are part of the scope of urban spatial planning and design, and have an immediate impact on and a direct relation to the accommodation of land use for the future growth of cities (Colding, 2007). However, high accident rates and hazardous activities in the AEC industry not only lead to a poor reputation but pose a threat to its future innovation and evolution. The scope of a risk is very broad and consists of issues such as damage or failure of structures, injury or loss of life, budget overruns, and delays to

the construction schedule, which are caused by various reasons such as design deficiency, material failure, inexperienced operatives, and weak management. For instance, in the United States, 503 bridge collapses were reported between 1989 and 2000 (Wardhana and Hadipriono, 2003), and according to official records over 26,000 workers lost their lives on construction sites from 1989 to 2013 (Zhang et al., 2013). It was estimated that over 60,000 on-site fatal accidents happen every year globally (ILO, 2005). In China, though the number of construction supervision companies has increased from 52 in 1989 to 5123 in 2000 (Liu et al., 2004), unwanted hazards related to safety, time, and cost were observed frequently due to poor risk management (Tam et al., 2004).

An AEC project starts with planning and design followed by the construction stage lasting for months or years, and eventually the project will come into the operation period that may last for decades before demolition. Different risks may be present in each of the different stages of the project and product lifecycle. There are a wide range of risks that may lead to hazards. In recent years, with the rapid development of society, risks are gradually growing because of the increasing structural complexity and project size,

* Corresponding author.

E-mail address: Yang.Zou@liverpool.ac.uk (Y. Zou).

and the adoption of new and complex construction methods (Shim et al., 2012). To reduce the possibility of these hazards occurring and to achieve project goals successfully, there is a high demand for managing risks effectively throughout a project's life cycle. However, the implementation of traditional risk management is still a manual undertaking, and the assessment is heavily reliant on experience and mathematical analysis, and decision making is frequently based on knowledge and experience based intuition, which leads to decreased efficiency in the real environment (Shim et al., 2012). In response to these problems, there is currently a new research trend of utilising Building Information Modelling (BIM) and BIM-related tools to assist in early risk identification, accident prevention, risk communication, etc., which is defined as "BIM-based risk management" in this paper.

The paper conducts a critical and extensive review on these new developments. It firstly presents an overview of the fundamentals, process, and challenges of the traditional risk management. This paper further moves on to discuss the state-of-the-art of the use of BIM and BIM-related technologies for risk management and outlines the existing challenges and gaps that slow down or prevent its broad adoption. The last part of the paper discusses combining traditional methods with new technologies and identifies research areas where additional research is needed in the future.

2. Research approach

2.1. Motivation and aim

The literature includes numerous studies describing the development of BIM and BIM-related technologies for managing particular risks (Chen and Luo, 2014; Hadikusumo and Rowlinson, 2004; Zhang and Hu, 2011; Zhang et al., 2013). Nearly all reviews (Bryde et al., 2013; Eastman et al., 2009; Forsythe, 2014; Hartmann et al., 2008; Zhou et al., 2012) partially summarise the application area, development and shortcomings of applying these technologies, and cover only one or several aspects separately. Many papers (Ahmed et al., 2007; Jannadi and Almishari, 2003; Vrouwenvelder et al., 2001; Zou et al., 2007) concentrate on reviewing traditional risk management methods and other publications (Azhar, 2011; Eastman et al., 2011; Tomek and Matějka, 2014) partially summarise the benefits and risks of implementing BIM in projects. However, to the authors' knowledge there is no comprehensive overview of recent research on BIM-based risk management as a comprehensive whole and no studies focusing on the relationship between digital technologies and the traditional methods for managing risk. The aim of this review is to close this gap, identify the obstacles of BIM-based risk management as well as foster research interests for the future.

2.2. Methodology

To review BIM-based risk management critically, a three-step approach was conducted. The topic of "risks of implementing BIM" and papers that are not published in English are not within the scope of this review.

In the first step, the fundamentals, general process, and main challenges of traditional risk management are summarised through an extensive literature review and several expert interviews for comprehensive understanding of the relation between the traditional methods and BIM-based risk management. The process identifies a set of keywords for data collection as the basis for the next step. The main keywords are, for example, "BIM", "building information model", "risk", "risk assessment", "risk analysis", "risk management", "knowledge management", "safety", "quality", "time", "cost", and "budget". In the second step these keywords

were applied to a web search in online academic publication databases, i.e. "Web of Science", "Engineering Village", "Scopus", and "Google Scholar", for collecting academic and applied publications related to this topic. Then the state-of-the-art of these technologies is classified and surveyed as follows: (1) BIM, (2) automatic rule checking, (3) knowledge based systems, (4) reactive IT-based safety systems (i.e. database technology, VR, 4D CAD, GIS), and (5) proactive IT-based safety systems (e.g. GPS, RFID, laser scanning). The scope of the survey includes articles in leading journals of this area (e.g. *Safety Science*, *Automation in Construction*, *International Journal of Project Management*, *Journal of Computing in Civil Engineering*, *Information Technology in Construction*, *Reliability Engineering & System Safety*), publications from conference proceedings and other sources of professional associations, standard committees (e.g. HSE, ISO) and authorities. In the third step, all publications are analysed critically and compared with the traditional risk management methods to identify current obstacles and future work to close these gaps.

3. Background

3.1. The fundamentals of risk management

The term "risk" was known in the English language from the 17th century and was derived from an original meaning to run into danger or to go against a rock (McElwee, 2007). Today the concept of risk is adopted in many different fields and with a variety of different words, such as "hazard", "threat", "challenge", or "uncertainty". In the AEC industry, risks have a two-edged nature, e.g. "the likelihood of unwanted hazards and the corresponding consequences" (Zou et al., 2007), "the likelihood and consequence of risks" (Williams, 1996), "a combination of the likelihood and consequences of the hazard" (Vrouwenvelder et al., 2001).

Risk management is a system aiming to recognise, quantify, and manage all risks exposed in the business or project (Flanagan and Norman, 1993). PMBOK® (Project Management Body of Knowledge) describes it as a process in relation to planning, identifying, analysing, responding, and monitoring project risks and one of the ten knowledge areas in which a project manager must be competent (PMI, 2004). The International Organization for Standardization (ISO, 2009) defines the process of risk management involving applying a systemic and logical method for establishing the context, creating a communication and consultation mechanism, and constructing risk management identification, analysis, evaluation, treatment, monitoring, and recording in a project. In accordance with these definitions, risk management in the AEC context is a logical, systematic, and comprehensive approach to identifying and analysing risks, and treating them with the help of communication and consultation to successfully achieve project goals. The systematic process includes risk identification, analysis, evaluation, treatment, monitoring and review (Banaitiene and Banaitis, 2012; ISO, 2009; Zou et al., 2007), where risk identification aims to find out the range of potential risks and risk analysis plays a core role in the whole process. When risks cannot be eliminated, early and effective identification and assessment of risks become necessary for effective risk management in a successful project (Zou et al., 2007). All activities of a project involve risks (ISO, 2009) and there is an immediate and direct relationship of objectives between the whole project and risk management.

A set of techniques has been developed to identify, analyse and evaluate risks. The techniques, according to ISO (2009), can be divided into qualitative and quantitative analysis. The former includes Delphi, check lists, strength–weakness–opportunity–threats (SWOT) analysis, risk rating scales, etc., while the latter includes environmental risk assessment, neural networks (NN),

row tie analysis, reliability centred maintenance, risk indices, and others. However, though the above methods are important techniques for risk management, they are confined to static control management and play only a limited role in practice (Zhang et al., 2014). The implementation of traditional risk management is still a manual undertaking, the assessment is heavily reliant on experience and mathematical analysis, and the decision making is frequently based on knowledge and experience based intuition, which always leads to a decreased efficiency in the real environment (Shim et al., 2012).

3.2. The general process of risk management

Based on a review of the literature, expert interviews, and the authors' own experience, the current general risk management framework used in the UK AEC industry is summarised in Fig. 1. The framework prescribes a long-term risk management strategy and a process that allows participants to work collaboratively to manage risks in a systematic way. The core philosophy of this method, defined in the Risk Mitigation Model, is that the main scope for identifying and mitigating risks should be as early as possible, especially in the design or planning phases, which is regulated in the UK's Construction Design and Management (CDM) Regulations 2007 (HSE, 2007). Ideally most of the foreseeable risks should be "designed out" during the planning or design stages, and the residual risks should be managed during the construction and subsequent phases.

However, some challenges in the above process are: (1) in-time knowledge capture and analysis, (2) the management of multi-disciplinary knowledge and experience, and (3) effective communication environment. Valuable knowledge and experience are gained from previous projects and this can be used to contribute to future work. In this case, the effective management of this large database of human knowledge and experience, as well as flexible and accurate data extraction, become a precondition for the success of risk management. As the project is handed over from designer to contractor, and then from contractor to the client, people will normally leave the project after completing their tasks and large amounts of risk information may be lost if it is not properly recorded and communicated to other project participants (Kazi, 2005).

3.3. Information and Communication Technologies (ICT) for risk management

To overcome these obstacles, ICT, e.g. BIM, 4D CAD, and Virtual Reality (VR), has been applied in the AEC industry to manage risks. For instance, construction safety risk planning and identification is an issue addressed by 3D/4D visualisation (Hartmann et al., 2008). BIM could help automatically detect physical spatial clashes (Chiu et al., 2011) and specific requirements of building codes could be interpreted to machine-read rules and checked automatically in Industry Foundation Classes (IFC) information models (Eastman et al., 2009). Li et al. (2013) presented a proactive monitoring system using Global Positioning System (GPS) in combination with

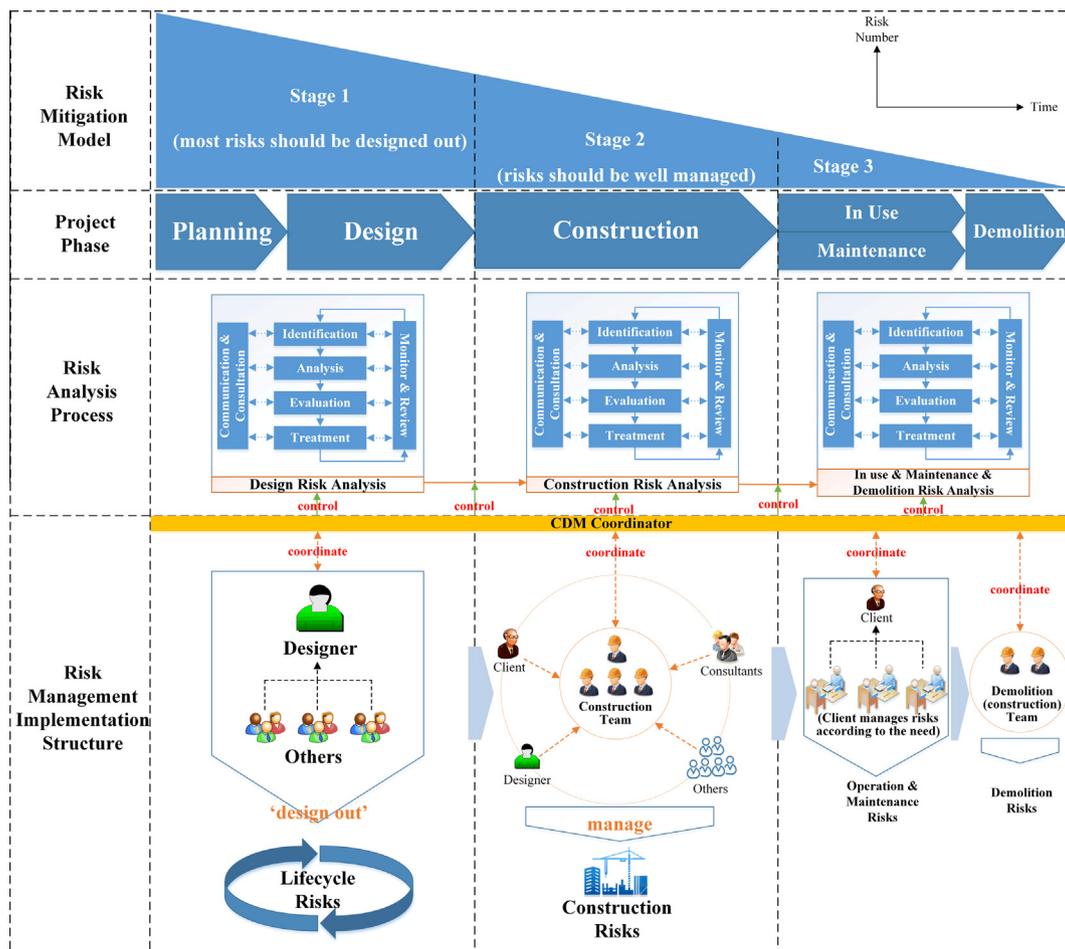


Fig. 1. General risk management framework.

Radio Frequency Identification (RFID) to improve the safety of blind lifting of mobile/tower cranes. The next section will review and discuss these developments critically in detail.

Two reasons could explain the increasing interest and adoption of ICT for risk management. The first reason is that as the industry has benefited from salient technical advantages of BIM and other digital technologies, a natural consequent is to investigate their possibilities in risk management. These new techniques could not only provide new design tools and management methods (Eastman et al., 2011) but significantly facilitate the collaboration, communication, and cooperation for both within and between organisations (Dossick and Neff, 2011), which are essential requirements for managing risks successfully. The second reason comes from a strong thrust from the government policy makers who have realised the importance of integrating ICT with risk management. Evidence of this is the new version of CDM regulations that will cover ICT such as BIM after 2015 (Joyce and Houghton, 2014) replacing the older version that was introduced in the UK initially in 1996 for improving safety and risk management.

4. Survey of BIM and BIM-related technologies for managing risks

The state-of-the-art of the use of BIM and BIM-related technologies for risk management is summarised in this section. The technologies referred here include BIM, automatic rule checking, knowledge based systems, reactive and proactive safety systems based on information technology. There is a distinct difference between reactive and proactive safety systems for risk management. Forsythe (2014) and Teizer et al. (2010) pointed out reactive systems using information technologies such as VR, 4D CAD, and GIS seldom use real-time data and need a post data collection processing effort for analysis, while in contrast proactive technologies can collect and analyse real-time data, and provide real-time warning and immediate feedback to construction site about dangers in time. It has been found that BIM, on one hand, can be used as a systematic risk management tool in the development process and, on the other, can perform as a core data generator and platform to allow other BIM-related tools for further risk analysis, where most of these technologies can be used interactively in related investigations.

4.1. Managing risks through BIM

Over the last few years, with the rapid development of theory and computer applications, BIM has achieved a remarkable awareness in the AEC industry and there is a significant increase of the adoption of BIM to support the planning, design, construction, operation and maintenance phases (Volk et al., 2014). Instead of being just considered as a technology, BIM is becoming a systematic method and process that is changing the project delivery (Porwal and Hewage, 2013), designing (Liu et al., 2014), and the communication and organisational management of construction (Hardin, 2011). Though most papers utilising BIM as an advanced tool to manage project risks such as design errors, quality, and budget do not often refer to risk management intentionally, the process of applying BIM can be seen, to some extent, as a systematic way for managing risks. Examples are presented in Table 1.

In the planning and design stages, one of the main risks is how the design aligns with the determined project feasibility, secured budget, and established governance regime (Miller et al., 2001). This is an area where BIM has the potential to manage the risks. For example, the visualisation of preliminary design by 3D/4D

Table 1
Examples for applying or developing BIM for risk management.

Functionality	Benefits for risk management	Research	Practice
3D visualisation	Facilitating early risk identification and risk communication	Hartmann et al. (2008)	Liu et al. (2014), Shim et al. (2012)
Clash detection	Automation of detecting physical conflicts in model	Hartmann et al. (2008), Tang et al. (2011)	Chiu et al. (2011), Liu et al. (2014)
4D construction scheduling/planning	Facilitating early risk identification and risk communication; improving construction management level	Hardin (2011), Hartmann et al. (2008), Whyte (2002)	Chiu et al. (2011), Liu et al. (2014)
5D cost estimation or cash flow modelling	Planning, controlling and managing budget and cost reasonably	Hardin (2011), Hartmann et al. (2008), Marzouk and Hisham (2014), Whyte (2002)	Motawa and Almarshad (2013)
Construction progress tracking	Improving management level for quality, safety, time, and budget	Bhatla et al. (2012), Eastman et al. (2011)	-
Safety management	Reducing personnel safety hazards	Teizer (2008), Whyte (2002)	-
Space management	Improving the consideration of space distribution and management in design	Hartmann et al. (2008), Kim et al. (2012)	-
Quality control	Improving construction quality	Chen and Luo (2014)	Liu et al. (2014)
Structural analysis	Improving structural safety	Lee et al. (2012b), Sacks and Barak (2008), Shim et al. (2012)	-
Risk scenario planning	Reducing personnel safety hazards	Azhar (2011), Hardin (2011)	Hartmann et al. (2012)
Operation and maintenance (Q&M), facility management (FM)	Improving management level and reducing risks	Becerik-Gerber et al. (2011), Volk et al. (2014)	-
Interoperability	Reducing information loss of data exchange	Ji et al. (2013), Laakso and Kivimäki (2012)	-
Collaboration and communication facilitation	Facilitating early risk identification and risk communication	Dossick and Neff (2011), Grillo and Jardim-Goncalves (2010), Porwal and Hewage (2013)	-
Urban planning and design	Integrating planning and design of urban space and AEC projects; facilitating land-use planning, design and management	Kim et al. (2011), Lee et al. (2012a), Rajabifard et al. (2012)	Lee et al. (2012a)

models could help engineers build and modify the model quickly in a parametric way to meet the stakeholders' requirements (Hartmann et al., 2008). The short videos or virtual walkthroughs which simulate the view of a person walking through the building can rapidly improve stakeholders' understanding of the project (Whyte, 2002). Meanwhile, neutral data formats such as the IFC that store standard and customised data for all project elements could provide an interoperable digital representation of all project elements enabling interoperability between BIM software applications (Laakso and Kiviniemi, 2012), which could increase the repeated use of data and reduce the possibility of errors.

At the construction stage, there is often a huge pressure for the construction team to complete the project safely within budget and schedule, and various risks and uncertainties exist in this period. To identify construction risks at an early stage and optimise the construction sequences, Chiu et al. (2011) conducted a clash detection and a 4D simulation of the construction of a steel bridge. Chen and Luo (2014) extended the 4D model to cover quality management based on construction codes and established a quality control model in a product, organisation and process (POP) data definition structure, which was used and validated in the construction of the Wuhan International EXPO centre. In addition, Marzouk and Hisham (2014) used BIM's ability of cost estimation to develop an application that integrates BIM with Earned Value (EV) for cost and schedule control, and determines the project status at specific reporting dates for infrastructure bridges.

It has also been found in this review that though the majority of efforts still focus on applying BIM to the design and construction phase, BIM can also be used in other processes and phases, e.g. facility management (Becerik-Gerber et al., 2011), maintenance management (Volk et al., 2014), and demolition (Cheng and Ma, 2013). In addition, a BIM-based collaboration and communication environment could naturally facilitate the early risk identification and mitigation (Dossick and Neff, 2011; Grilo and Jardim-Goncalves, 2010).

4.2. Knowledge based systems

In the AEC industry, every project produces valuable knowledge and experience which can contribute significantly to managing risks in future projects. It is essential to manage this information properly and communicate it effectively in all stages of the whole project lifecycle (Tah and Carr, 2001). This idea has been recognised and adopted for a long time by researchers to manage project risks. For example, Total-Safety (Carter and Smith, 2006) is a method statement development module within an ICT tool that could assist engineers to formulate method statements with a high level of risk identification by extracting safety information from a knowledge based database. When a construction method is chosen, the tool can return all known risks associated with different tasks as the knowledge basis for further risk assessment. Similarly, Cooke et al. (2008) proposed a web-based decision support program named ToolSHed to integrate assessment of safety risk into design process. The principle of ToolSHed is to structure the knowledge obtained from industry standards, national guidelines and codes of Australia, and other information sources, and employ this knowledge for assessing risks in complicated situations of buildings.

The integration of BIM and knowledge based systems has been seen as a new trend. Deshpande et al. (2014) proposed a new method to capture, extract, and store information and knowledge from BIMs, and presented a framework for classification and dissemination of the knowledge. To strengthen its practical application, Ho et al. (2013) developed a BIM-based Knowledge Sharing Management (BIMKSM) system that could enable managers and engineers to share knowledge and experience in the BIM environment.

Aiming at managing safety risks in design, Qi et al. (2011) developed a dictionary of construction worker suggestions and a constraint model to store the formalised suggestions. Then in the BIM environment, designers could utilise rule checking software for identifying safety risks during the planning and design phases, and mitigating risks and optimising their designs. The system consists of three parts: BIM as the main information input, a knowledge based system, and a risk identification module. Motamedi et al. (2014) integrated the use of knowledge management (KM) and BIM to investigate an approach for detecting failure root-cause which could help facility management (FM) technicians identify and solve problems from their cognitive and perceptual reasoning. Integrated with BIM, a Computerised Maintenance Management System (CMMS) was developed to store inspection and maintenance data. In addition, a knowledge based BIM system was presented by Motawa and Almarshad (2013) to capture and store various types of information and knowledge created by different participants in the construction project in order to support decision making for building maintenance.

4.3. Automatic rule checking

In definition, the term *Automatic Rule Checking* is the use of a computer program to assess a design based on objects' configuration (Eastman et al., 2009) and its purpose is to encode rules and criteria by interpretation and thus building models could be checked against these machine-read rules automatically with results, for example, "pass", "fail", "warning", or "unknown" (Borrmann et al., 2009).

Regulations and rules written by experts have traditionally been comprehended, interpreted and used in a manual way. Thus, these rules are sometimes conflictive and incomplete, and the corresponding implementation is often limited by people's understanding, interpretation, and reasoning capability. To computerise this process and improve the effectiveness, the research of automatic code checking or rule compliance started in the 1960s. Soon afterwards, a lot of effort was put into interpreting particular requirements to computerised codes, logically structuring and managing rules, and developing rule-based systems (Fenves, 1966; Fenves et al., 1995; Garrett and Fenves, 1987; Rasdorf and Lakmazaheri, 1990). In the late 1990s, due to the fast growth rule-based systems for building models, the development of IFCs brought on the initial exploration of building model schema for checking building codes. This review has observed three development directions in the area of automatic rule checking during the last two decades – (1) building design codes compliance, (2) construction safety checking, and (3) special requirements checking, which will be discussed further in detail below. A comprehensive review, which introduced the main steps and software platforms of automatic rule checking, was reported by Eastman et al. (2009).

The most common application of rule checking is to ensure the design work is compliant with numerous building codes which are normally known as the minimum standards for construction objects such as buildings and infrastructure projects. To computerise this work, two major activities are needed to achieve this goal: (1) to formalise the building code and BIM into building rule models and building design representation models respectively; and (2) to implement both models in computer programs and execute rule objects over design objects in compliance checking automatically (Yang and Xu, 2004). Substantial efforts in this area have been made in recent years. For example, Delis and Delis (1995) proposed a method which could encode fire code requirements in a knowledge based system for analysing the performance of fire safety in the completed building design. Balachandran et al. (1991) developed an approach to processing non-measurable code provisions for verifying building designs automatically. Solihin (2004)

developed the e-PlanCheck system by using the IFC model and Express Data Manager (EDM) for assessing the code compliance in Singapore. One of the latest efforts in this area is an on-going project in the US funded by Fiatch to develop AutoCodes expecting to improve automatic code checking capability for BIM standards and guidelines, and US building model codes (Fiatch, 2013).

The second development direction is to check construction safety rules. To prevent any human safety accidents on site, it is essential to identify and mitigate these risks in design, and inspect, monitor and manage safety in construction. Hence the design stage is the best opportunity to mitigate most of these risks if potential hazards could be well identified and planned, and corresponding measures to control these risks can be chosen correctly (Bansal, 2011). Yi and Langford (2006) collected and analysed historical safety records and proposed a theory that could estimate a project's risk distribution. Sulankivi et al. (2013) presented a theory to identify safety risks which are unknowingly built into the construction activities at the design stage and developed a BIM-based automatic safety rule-checking prototype. The approach works by simulating the construction sequences and tasks with embedded safety rules. Aiming at fall protection, Zhang et al. (2013) formalised the fall protection rules of the Occupational Safety and Health Administration (OSHA) and other best practices into a table-based safety rule translation algorithm, and implemented a rule-based checking system in BIM to plan and simulate safety issues at an early stage. The feasibility has been shown by implementing this approach in Tekla Structures.

The last application direction of development is for checking specific requirements of buildings, such as the circulation problems, space requirements, and special site considerations. For instance, Han et al. (2002) presented a hybrid method that used encoding prescriptive-based provisions and supplemented them with a performance-based approach to facilitate conformance and applicability analysis for accessibility. Lee (2010) developed a new approach to checking occupant circulation rules automatically in the US Courts Design Guide, which could assist circulation rule checking in the development processes of a courthouse's design. Lee et al. (2010) proposed a computational approach called the Universal Circulation Network (UCN) for checking walking distances between buildings by implementing a length-weighted graph structure for building models, and developed a plug-in on top of the Solibri Model Checker.

4.4. Safety risk management through reactive IT-based safety systems

The AEC industry is still faced with a particular challenge of high accident rates – over 6 percentage in Hong Kong for instance (OSHC, 2008). To detect health and safety (OHS) risks in time and mitigate them before any hazards occur, reactive IT-based safety systems have been used in conjunction with BIM to achieve this goal. Forsythe (2014) and Zhou et al. (2012) summarised these technologies including, for example, database technology, Virtual Reality (VR), 4D CAD, Geographic Information Systems (GIS), which are discussed in this sub-section.

4.4.1. Database technology

Experience and knowledge learned from past accidents provide a better perception to prevent hazards in future work (Gambatese et al., 2005). An obvious step from this is database technology that could be used to store valuable knowledge, capture accurate information and then intelligently extract them based on specific selection criteria (Forsythe, 2014). For example, Imhof (2004) collected 360 cases of bridge failures and established an online database to help learn from past accidents, analyse the risk distribution and summarise the main risk factors that led to bridge collapse, which allows a better understanding of the mechanism of an accident and

a better insight of how to prevent hazards in the future. Yu (2009) developed a knowledge based decision support model on the basis of knowledge representation and reasoning features to assist clients to evaluate competence of potential designers, principal contractors, and CDM coordinators. Furthermore, to improve the performance and capability, an enhanced online database called Construction Safety and Health Monitoring (CSHM) system was developed to enable remote access, speedy data collection and retrieval, and expert communication (Cheung et al., 2004).

4.4.2. Virtual reality

Virtual Reality (VR) is an important area in current BIM research and vice versa (Gu and London, 2010). Conceptually, VR is a virtual system that consists of a computer capable of real-time animation, controlled through a group of equipment for simulating physical presence in places in the real world (Steuer, 1992). VR has been used to provide a 3D, virtual and interactive computer environment for training site workers to become aware of identified on-site safety risks (e.g. (Guo et al., 2012)) and formalising strategies and measures of potential hazards by simulating the dangerous scenarios (e.g. (Wang et al., 2014)). Specifically, Guo et al. (2012) presented a game based interactive multi-client platform for safety training to improve construction site operation safety. Embedded with identified hazards, the platform provides a virtual environment where trainees can learn and practice operating methods and construction sequences, which closely resemble the real working on-site environment. The presented platform also encourages trainees to work collaboratively with others in operating the construction site. Though technological development looks extremely important in VR for managing safety risks, how these developed technologies could be adopted and implemented in practice becomes another concern. Therefore, after summarising the main factors that may cause construction accidents, Guo et al. (2013) proposed a conceptual framework to adopt Virtual Prototyping (VP), consisting of three core components: (1) modelling and simulation, (2) identification of unsafe factors, and (3) safety training, to support construction health and safety risk management for both technicians and workers. For improving the building emergency management, Wang et al. (2014) developed a BIM based virtual environment (BIM-VE) to address two key issues: “(1) timely two-way information flow and its applications during the emergency and (2) convenient and simple way to increase evacuation awareness”. In addition, VR can also be incorporated with database technology for managing construction safety risks. For example, Hadikusumo and Rowlinson (2002, 2004) created a design-for-safety-process (DFSP) tool to aid safety risk identification when producing the construction plans and schedules in the design stage. This tool comprises three components: (1) the DFSP database, (2) the virtual reality construction components and processes, and (3) virtual reality functions. The DFSP database stores a full list of common dangerous conditions and actions, local accident reports and rules. The integration of the VR components and DFSP database allows users to walk through in a virtual project environment from a first-person view and to identify safety risks within construction components and related processes, and to choose preventative measures for those identified risks.

4.4.3. 4D CAD

Early research of applying four-dimensional computer aided design (4D CAD) for construction planning to identify potential problems, mitigate risks, and optimise construction schedule and processes started in the early 1990s (Heesom and Mahdjoubi, 2004). The core concept of 4D CAD is to add 4D construction schedule information into a 3D model to establish a collaboration and communication media and clear visual insights of the construction sequences for the construction team (Koo and Fischer, 2000). It is

observed that the most common application of 4D CAD for safety risk management is to establish an extensive 4D CAD model by gathering all design data about building objects and construction processes, activities and sequences, and conduct further risk analysis on the basis of the model. For instance, [Benjaoran and Bhokha \(2010\)](#) presented a 4D CAD model to integrate safety risk and construction management. Rule-based algorithms for working-at-height risks were formalised, interpreted, and visualised into the model. A rule-based system was then used to extract information from the 4D CAD model to detect working-at-height risks automatically and forecast necessary measures including safety activities and requirements. In structural analysis, Hu and Zhang proposed a new method in their two papers ([Hu and Zhang, 2011](#); [Zhang and Hu, 2011](#)) to analyse safety and conflict by incorporating BIM, 4D CAD, time-dependent structural analysis, and clash detection, and then implemented this theoretical solution by developing an integrated archetypal system named 4D-GCPSU 2009. A group of researchers from Finland's VTT Technical Research Centre demonstrated a BIM-based safety management and communication system that develops construction procedures and BIM for 4D safety planning, management, and communication, where BIM and 4D CAD are utilised as the central technologies ([Kiviniemi et al., 2011](#)).

4.4.4. Geographic information systems

While BIM is defined to develop objects' geometric data into the maximum level of detail, a Geographic Information System (GIS) is a collection of environmental information from the macro perspective ([Irizarry and Karan, 2012](#); [Zhou et al., 2012](#)). GIS can be integrated into a Decision Support System (DSS) to monitor and control safety risks ([Cheng et al., 2002](#)). Along a similar line, [Bansal \(2011\)](#) successfully applied GIS to predict places and activities where there was an increased likelihood of hazards in a building project in India because BIM and 4D modelling could not provide the capability for features like 3D components editing, topography modelling, geospatial analysis, and generation and updating of schedules. [Bansal and Pal \(2007\)](#) also proved GIS has the potential to help cost estimation and visualisation. Recently, several studies have been conducted to explore how to integrate BIM and GIS to improve construction site safety risk management and optimisation. For example, [Irizarry and Karan \(2012\)](#) integrated the use of BIM and GIS and proposed a GIS–BIM model to assist identification and optimisation of the feasibility for the location of tower cranes. In this work, BIM software was first used to generate geometry information of the construction site, and the GIS model then extracted data from the BIM to determine the proper combination of tower cranes for location optimisation. The analysis output linking to the BIM platform can suggest one or more possible areas including all supply points and demand.

4.5. Proactive IT-based safety systems

As described in the previous sections, reactive IT-based safety systems are able to provide 4D simulation and virtual prototyping to assist safety risk identification and construction safety management planning. However, as planning is by nature a predictive process established on previous knowledge and experience, the construction projects have a habit of changing during the dynamic processes of project lifecycle ([Forsythe, 2014](#)). To manage those unplanned changes and unexpected safety risks, it is important to track the hazard areas, collect real-time data from the sites for further analysis, and give immediate warning or feedback to the active construction workspace before the actual occurrence of hazards, which is what proactive IT-based safety systems could help ([Teizer et al., 2007](#)). To achieve this objective, proactive IT-based safety systems can be created by combining one or more

information technologies, BIM, and possibly other techniques. [Teizer et al. \(2007\)](#) and [Forsythe \(2014\)](#) summarised the related technologies, approaches, their features, and current situation and development. The core philosophy behind proactive IT-based safety systems is to create a virtual environment where accurate positions of both static and moving objects can be tracked, the corresponding data from the real world can then be collected in real time and analysed by formalised safety algorithms, and, most importantly, information of hazards could be delivered in real-time and effective mitigation measures can be taken in time.

Currently, most efforts of proactive IT-based safety systems focus on tracking the static and moving objects in particular construction activities such as excavator and crane usage. For example, [Kim et al. \(2004\)](#) presented a theoretical model of a human-assisted obstacle-avoidance system with a 3D workspace model, and a sparse point cloud approach was described for modelling static objects or zones which may lead to hazards or have been identified to have risks. The framework includes algorithms for obstacle avoidance system as well as for 3D workspace modelling. To apply this theory, [McLaughlin et al. \(2004\)](#) developed an obstacle detection system to allow machines to navigate around equipment safely. Radio frequency wave spectrum technology was applied by [Allread \(2009\)](#) to warn workers in real time where blind spots occur for machine operators and when they are in danger. To improve the safety of blind lifting of mobile/tower cranes, [Li et al. \(2013\)](#) presented a real-time monitoring system which integrates the use of Radio Frequency Identification (RFID) and Global Positioning System (GPS). The system can detect the interactive proximity between unauthorised work or the entrance of personnel and the crane. When workers were present within a risk zone, a warning was sent to the safety management team. Other proactive technologies have been used in this area including, laser scanning ([Cheng and Teizer, 2014](#)), remote sensing and actuating technology ([Teizer et al., 2010](#)), and wireless communication ([Wu et al., 2013](#)).

In order to improve the tracking accuracy and reliability, [Teizer et al. \(2013\)](#) used Ultra-Wideband (UWB) to deal with the indoor and outdoor settings and to provide the 3D and 4D location values accurately in real time. To enhance the risk management in large transit projects, [Ding and Zhou \(2013\)](#) developed a web-based system for safety early warning in urban metro construction. From this review, it has also been observed that sensors receiving passive warning signals are commonly embedded into Personal Protective Equipment (PPE), such as safety helmets, hats, and shoes, for enhancing the portability of these warning devices, e.g. ([Abderrahim et al., 2005](#); [Teizer et al., 2010](#)).

4.6. Implications of BIM-based risk management

The purpose of this section is twofold: (1) to provide an overview discussion of BIM-based risk management, and (2) to summarise the shortcomings of related technologies.

The literature shows that BIM and numerous BIM-related digital technologies have been developed to assist risk management during a project's lifecycle. These technologies, discussed in the previous sub-sections, include BIM, automatic rule checking, knowledge based systems, reactive and proactive safety systems. Applications managing some particular risks can be developed based on either a single technology or a combination of several technologies as illustrated, for instance, in the 4D-GCPSU 2009 system. What can be seen from all of the above efforts is that there has been an emphasis on identifying and mitigating risks as early as possible, and managing real-time risks before any occurrences of hazards. Meanwhile, the findings show that despite considerable developmental work, most of their focus has been on exploiting new technologies to mitigate single risks in particular scenarios

for design and construction stages, such as the prevention of falling accidents through automatic rule checking. The management of construction personnel safety risk is a main interest so far, e.g. in Sections 4.4 and 4.5.

However, there is a need to point out that most existing studies are at a conceptual or prototyping stage because of existing limitations. For example, an important challenge for knowledge based systems is how to ensure the knowledge and experience shared by a limited number of professionals are complete and “correct” information of the potential risks. Though in current AEC projects, successful project risk management is still heavily reliant on all participants’ experience and knowledge, as discussed in Section 3.2, different people have different educational backgrounds, knowledge bases, and project experience, and the process of risk management through knowledge sharing is naturally complicated. Eastman et al. (2009) highlighted three main problems in current automatic rule checking systems: (1) most common rule checking systems rely on IFC as input and currently are limited in what they support; (2) rule checking at the scale of all sections of a project’s codes is a massive undertaking. A critical problem is how to identify and verify the potential errors in the rule checking algorithms and building models; (3) current efforts enable checking the final state of a design but fail to support its development process. Though several reactive IT-based safety systems have been applied for safety risks planning before actual operation, as described in Section 4.4, a significant shortcoming exists. The planning process is by nature established on knowledge and experience-based human assumptions. As construction is a dynamic process which may last for many years and involves frequently unexpected changes and unplanned risks, operational risk management cannot normally fully comply with the original planning. Regarding this issue, an additional method is to work on a collaborative 4D construction planning platform by collecting as much reliable multi-discipline knowledge and experience as possible (Zhou et al., 2009). Another alternative approach is to use proactive technologies for real-time data collection and treatment, as described in Section 4.5. However, much of the cited work on proactive systems is still very young. Some particular hazardous scenarios in, for example, excavation and lifting have been considered. Meantime, so far most of these efforts only focus on technical development, and these technologies have not reached the stage of “human factor” testing (Forsythe, 2014). Therefore there is still a long way to go before the wide use of these new technologies for risk management will be common in the workplace.

5. Discussion

An important aspect of this research is to find out challenges and research gaps in current BIM-based risk management through a systematic and critical review, which is discussed as follows:

5.1. A multi-disciplinary system-thinking

This review indicates that developing new technologies to assist with the management of construction safety risks is currently a popular research topic. However, any AEC project starts with planning and design followed by the construction stage lasting for months or years, and eventually the project will come into the operation period that may last for decades before demolition. Various types of risks (e.g. structural safety risk, financial risk, environmental risk, supply risk) may be present in the different stages of the project and product lifecycle. People with different knowledge background and from different domains may be involved in the dynamic process of risk management. ISO (2009) stated that “*risk management is a logic and systematic method*”. Hence, it is clear that

the concept of multi-disciplinary system-thinking should be embedded in the research of BIM-based risk management.

5.2. Implementation method and process

The findings show that despite considerable development work, much of the focus has been on exploiting and developing new technologies to treat specific risks in a particular scenario, which were also mentioned by Zhou et al. (2012) and Forsythe (2014). Since AEC projects are one-off endeavours with numerous special features and risks existing during the whole dynamic process, any new methods for risk management are valuable when core project participants start to use these enhanced technologies as part of their daily work. The complete implementation framework or method of BIM-based risk management consisting of fragmented activities and processes are equally important as technical developments. Finally the people, who work collaboratively in a project team using these technologies for managing risks, make the projects successful, and profitable. Based on these observations, an important research topic is to investigate how BIM and BIM-related technologies can be implemented in real projects to achieve their best value.

5.3. Integration of BIM-based and traditional methods for risk management

Another knowledge gap observed in this review is that there are nearly no studies focusing on integrating BIM and BIM-related digital technologies with the traditional methods, processes, and techniques for risk management. Numerous investigations (Hartmann et al., 2012; Shim et al., 2012; Zhang et al., 2014) have pointed out that the traditional method is heavily reliant on experience and multi-disciplinary knowledge, and common risk assessment techniques include Fault Tree Analysis (FTA) (Suresh et al., 1996), decision trees (Dey, 2002), and neural networks (NN) (Khoshgoftaar and Lanning, 1995), etc. These general methods have been commonly applied by the AEC industry and play a significant role in real projects. Clearly, there is a need to combine BIM-based and traditional risk management to improve practical applicability. The potential and benefits have been proved by several instances. For example, Shim et al. (2012) converted the traditional risk management method into visual information in a visualisation environment to improve the efficiency for practitioners in dynamic risk management in terms of schedule, cost and safety to assist the design and construction and management of a challenging cable stayed bridge project. Another study, from a “technology pull” perspective, aligned BIM with risk management into a large infrastructure project to test its practical performance (Hartmann et al., 2012).

5.4. BIM-based risk management as part of the development process

Undoubtedly risks may be present in the different stages of the project and product lifecycle and the performance of risk management has a direct influence on whether the project can be fulfilled successfully on-time and within budget. In the UK, the CDM rules are a compulsory legislation requirement that indicates all risk analysis for a project starts with the designer. It is the designer who has to assess the risks that may occur during the construction, use of the project, maintenance (including equipment replacement), and demolition. It is the responsibility of the designer to “design out” and eliminate the risks wherever possible. If this is not possible it is the responsibility of the designer to minimise the risks. When a contractor is appointed, the analysis of risks continues but now with the assistance of specialists in construction. A

construction project is normally divided into a number of sub-projects for managing risks at a sub-project level by considering different activities and processes individually. Each sub-project may have separate designers and contractors with their own risks to identify and manage. A group of risk specialists (experts from multi-disciplines) hired by the project team then need to collaborate with project members to identify and investigate the potential risks by interviews and discussions. A group of paper-based risk documents (e.g. risk start-up report, risk inventory) are then compiled in this process. To implement risk management, specialists who play facilitating roles during the risk management process need to attend the project control meetings and keep tracking progress, and give advice on specific construction activities. However, the project team, especially the managers, is required to be responsible for the application of the risk management cycle. It is extremely important to point out that many people will be involved in the risk management during the lifecycle, so that any updated risk information, decisions and changes should be recorded and communicated effectively. Therefore, BIM-based risk management is expected to facilitate efficient risk communication and support the dynamic development process of a project.

6. Conclusion

Utilising BIM and BIM-related digital technologies to manage risks has been a growing research interest in the AEC industry. Successful use of these technologies requires a comprehensive understanding of the fundamentals, general process, techniques of risk management and the relationship between the new and traditional methods.

This paper summarises the current status and challenges of traditional risk management and has conducted a systematic and critical literature review on the state-of-the-art of BIM-based risk management, and discussed the current obstacles and future needs. The literature shows the implementation of traditional risk management is still a manual undertaking, the assessment is heavily reliant on experience and mathematical analysis, and the decision making is frequently based on knowledge and experience based intuition, which leads to a decreased efficiency in the real environment. To improve the above situation, some standards or governmental documents (e.g. ISO 31010:2009, CDM regulations) put emphasis on foreseeable risks being identified and mitigated at an early stage and risk information should be documented and updated during the development process of a project. This is where BIM could be of help. BIM could not only be used as a systematic risk management tool in the development process, but also act as a core data generator and platform to allow other BIM-based tools to carry out further risk analysis. The tools reviewed in this paper include automatic rule checking, knowledge based systems, reactive and proactive IT-based safety systems. The findings indicate that most of the current efforts focus on investigating technical developments and the management of construction personnel safety risks is a main interest so far. Because BIM-based risk management is an emerging development, there are still some technical limitations and lack of 'human factor' testing in practice. Therefore, these efforts are still at a conceptual or prototyping stage and have not been broadly used in real workplaces. To overcome this gap, we suggest future research should: (1) have a multi-disciplinary system-thinking, (2) investigate implementation methods and processes, (3) integrate traditional risk management with new technologies, and (4) support the project development process. In conclusion, though the area of BIM-based risk management is just emerging and there is no 'complete' solution so far, the area is important and will provide interesting opportunities in the future.

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References

- Abderrahim, M., Garcia, E., Diez, R., Balaguer, C., 2005. A mechatronics security system for the construction site. *Automat. Constr.* 14, 460–466.
- Ahmed, A., Kayis, B., Amornsawadwatana, S., 2007. A review of techniques for risk management in projects. *Benchmarking: Int. J.* 14, 22–36.
- Allread, B.S., 2009. Real-time pro-active safety in construction. MSc Dissertation, Georgia Institute of Technology, Atlanta, USA.
- Azhar, S., 2011. Building information modeling (BIM): trends, benefits, risks, and challenges for the AEC industry. *Leadership Manage. Eng.* 11, 241–252.
- Balachandran, M., Rosenman, M., Gero, J., 1991. A knowledge-based approach to the automatic verification of designs from CAD databases. In: *Artificial Intelligence in Design*. Butterworth-Heinemann Oxford, pp. 757–781.
- Banaitiene, N., Banaitis, A., 2012. Risk management in construction projects. In: Banaitiene, N. (Ed.), *Risk Management—Current Issues and Challenges*. Intech, pp. 429–448.
- Bansal, V., 2011. Application of geographic information systems in construction safety planning. *Int. J. Project Manage.* 29, 66–77.
- Bansal, V.K., Pal, M., 2007. Potential of geographic information systems in building cost estimation and visualization. *Automat. Constr.* 16, 311–322.
- Becerik-Gerber, B., Jazizadeh, F., Li, N., Calis, G., 2011. Application areas and data requirements for BIM-enabled facilities management. *J. Constr. Eng. Manage.* 138, 431–442.
- Benjaoran, V., Bhokha, S., 2010. An integrated safety management with construction management using 4D CAD model. *Saf. Sci.* 48, 395–403.
- Bhatla, A., Choe, S.Y., Fierro, O., Leite, F., 2012. Evaluation of accuracy of as-built 3D modeling from photos taken by handheld digital cameras. *Automat. Constr.* 28, 116–127.
- Borrmann, A., Hyvärinen, J., Rank, E., 2009. Spatial constraints in collaborative design processes. In: *Proceedings of the International Conference on Intelligent Computing in Engineering (ICE09)*, Berlin, Germany, pp. 1–8.
- Bryde, D., Broquetas, M., Volm, J.M., 2013. The project benefits of Building Information Modelling (BIM). *Int. J. Project Manage.* 31, 971–980.
- Carter, G., Smith, S.D., 2006. Safety hazard identification on construction projects. *J. Constr. Eng. Manage.* 132, 197–205.
- Chen, L., Luo, H., 2014. A BIM-based construction quality management model and its applications. *Automat. Constr.* 46, 64–73.
- Cheng, J.C., Ma, L.Y., 2013. A BIM-based system for demolition and renovation waste estimation and planning. *Waste Manage.* 33, 1539–1551.
- Cheng, M.Y., Ko, C.H., Chang, C.H., 2002. Computer-aided DSS for safety monitoring of geotechnical construction. *Automat. Constr.* 11, 375–390.
- Cheng, T., Teizer, J., 2014. Modeling tower crane operator visibility to minimize the risk of limited situational awareness. *J. Comput. Civ. Eng.* 28, 04014004.
- Cheung, S.O., Cheung, K.K., Suen, H.C., 2004. CSHM: web-based safety and health monitoring system for construction management. *J. Saf. Res.* 35, 159–170.
- Chiu, C.-T., Hsu, T.-H., Wang, M.-T., Chiu, H.-Y., 2011. Simulation for steel bridge erection by using BIM tools. In: *28th International Symposium on Automation and Robotics in Construction, ISARC 2011*, IIT Madras, Seoul, Republic of Korea, pp. 560–563.
- Colding, J., 2007. 'Ecological land-use complementation' for building resilience in urban ecosystems. *Landscape Urb. Plann.* 81, 46–55.
- Cooke, T., Lingard, H., Blismas, N., Stranieri, A., 2008. ToolSheDTM: the development and evaluation of a decision support tool for health and safety in construction design. *Eng., Constr. Archit. Manage.* 15, 336–351.
- Delis, E.A., Delis, A., 1995. Automatic fire-code checking using expert-system technology. *J. Comput. Civ. Eng.* 9, 141–156.
- Deshpande, A., Azhar, S., Amireddy, S., 2014. A framework for a BIM-based knowledge management system. *Proc. Eng.* 85, 113–122.
- Dey, P.K., 2002. Project risk management: a combined analytic hierarchy process and decision tree approach. *Cost Eng.* 44, 13–27.
- Ding, L.Y., Zhou, C., 2013. Development of web-based system for safety risk early warning in urban metro construction. *Autom. Constr.* 34, 45–55.
- Dossick, C.S., Neff, G., 2011. Messy talk and clean technology: communication, problem-solving and collaboration using Building Information Modelling. *Eng. Proj. Org. J.* 1, 83–93.
- Eastman, C., Lee, J., Jeong, Y., Lee, J., 2009. Automatic rule-based checking of building designs. *Autom. Constr.* 18, 1011–1033.
- Eastman, C., Teicholz, P., Sacks, R., Liston, K., 2011. *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*. John Wiley & Sons, USA.
- Fenves, S.J., 1966. Tabular decision logic for structural design. *J. Struct. Div.* 92, 473–490.
- Fenves, S.J., Garrett, J., Kiliccote, H., Law, K., Reed, K., 1995. Computer representations of design standards and building codes: US perspective. *Int. J. Constr. Inform. Technol.* 3, 13–34.
- Fiatch, 2013. *An Overview of Existing BIM Standards and Guidelines: A Report to Fiatch AutoCodes Project*. Construction Industry Institute, The University of Texas, Austin, USA.

- Flanagan, R., Norman, G., 1993. Risk Management and Construction. Blackwell Scientific, Oxford.
- Forsythe, P., 2014. Proactive construction safety systems and the human factor. *Proc. Inst. Civ. Eng.: Manage., Procurement Law* 167, 242–252.
- Gambatese, J.A., Behm, M., Hinze, J.W., 2005. Viability of designing for construction worker safety. *J. Constr. Eng. Manage.* 131, 1029–1036.
- Garrett Jr., J.H., Fenves, S.J., 1987. A knowledge-based standards processor for structural component design. *Eng. Comput.* 2, 219–238.
- Grilo, A., Jardim-Goncalves, R., 2010. Value proposition on interoperability of BIM and collaborative working environments. *Autom. Constr.* 19, 522–530.
- Gu, N., London, K., 2010. Understanding and facilitating BIM adoption in the AEC industry. *Autom. Constr.* 19, 988–999.
- Guo, H., Li, H., Chan, G., Skitmore, M., 2012. Using game technologies to improve the safety of construction plant operations. *Accid. Anal. Prev.* 48, 204–213.
- Guo, H.L., Li, H., Li, V., 2013. VP-based safety management in large-scale construction projects: a conceptual framework. *Autom. Constr.* 34, 16–24.
- Hadikusumo, B.H.W., Rowlinson, S., 2002. Integration of virtually real construction model and design-for-safety-process database. *Autom. Constr.* 11, 501–509.
- Hadikusumo, B.H.W., Rowlinson, S., 2004. Capturing safety knowledge using design-for-safety-process tool. *J. Constr. Eng. Manage.* 130, 281–289.
- Han, C.S., Kunz, J.C., Law, K.H., 2002. Compliance analysis for disabled access. In: *Advances in Digital Government*. Springer, pp. 149–162.
- Hardin, B., 2011. BIM and Construction Management: Proven Tools, Methods, and Workflows. John Wiley & Sons, Indiana, USA.
- Hartmann, T., Gao, J., Fischer, M., 2008. Areas of application for 3D and 4D models on construction projects. *J. Constr. Eng. Manage. – ASCE* 134, 776–785.
- Hartmann, T., Van Meerveld, H., Vossebeld, N., Adriaanse, A., 2012. Aligning building information model tools and construction management methods. *Autom. Constr.* 22, 605–613.
- Heesom, D., Mahdjoubi, L., 2004. Trends of 4D CAD applications for construction planning. *Constr. Manage. Econom.* 22, 171–182.
- Ho, S.P., Tserng, H.P., Jan, S.H., 2013. Enhancing knowledge sharing management using BIM technology in construction. *Sci. World J.* 2013, 170498.
- HSE, 2007. The Construction (Design and Management) Regulations. Health and Safety Executive (HSE), London.
- Hu, Z., Zhang, J., 2011. BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 2. Development and site trials. *Autom. Constr.* 20, 167–180.
- ILO, 2005. Fact Sheet on Safety at Work. International Labour Organization, Geneva, Switzerland.
- Imhof, D., 2004. Risk Assessment of Existing Bridge Structures. PhD Thesis, University of Cambridge.
- Irizary, J., Karan, E.P., 2012. Optimizing location of tower cranes on construction sites through GIS and BIM integration. *Electron. J. Inform. Technol. Constr.* 17, 361–366.
- ISO, 2009. Risk Management – Risk Assessment Techniques, IEC/FDIS 31010:2009, International Organization for Standardization.
- Jannadi, O.A., Almishari, S., 2003. Risk assessment in construction. *J. Constr. Eng. Manage.* 129, 492–500.
- Ji, Y., Borrmann, A., Beetz, J., Obergriesser, M., 2013. Exchange of parametric bridge models using a neutral data format. *J. Comput. Civ. Eng.* 27, 593–606.
- Joyce, R., Houghton, D., 2014. Briefing: building information modelling and the law. *Proc. ICE – Manage., Procurement Law* 167, 114–116.
- Kazi, A.S., 2005. Knowledge Management in the Construction Industry: A Socio-Technical Perspective. IGI Global, USA.
- Khoshgoftaar, T.M., Lanning, D.L., 1995. A neural network approach for early detection of program modules having high risk in the maintenance phase. *J. Syst. Softw.* 29, 85–91.
- Kim, C., Haas, C.T., Liapi, K.A., McLaughlin, J., Teizer, J., Bosche, F., 2004. Rapid human-assisted, obstacle avoidance system using sparse range point clouds. In: Malla, R.B., Maji, A. (Eds.), *Engineering, Construction and Operations in Challenging Environments: Earth and Space 2004*. American Society of Civil Engineers, New York, pp. 115–122.
- Kim, J.B., Clayton, M.J., Yan, W., 2011. Parametric Form-Based Codes: Incorporation of Land-use Regulations into Building Information Models, Parametricism (SPC) ACADIA Regional 2011 Conference. Lincoln, Nebraska, United States, pp. 217–223.
- Kim, T.W., Kavousian, A., Fischer, M., Rajagopal, R., 2012. Improving Facility Performance Prediction by Formalizing an Activity-Space-Performance Model. CIFE Technical Paper 210.
- Kiviniemi, M., Sulankivi, K., Kähkönen, K., Mäkelä, T., Merivirta, M.-L., 2011. BIM-Based Safety Management and Communication for Building Construction. VTT, Finland.
- Koo, B., Fischer, M., 2000. Feasibility study of 4D CAD in commercial construction. *J. Constr. Eng. Manage.* 126, 251–260.
- Laakso, M., Kiviniemi, A., 2012. The IFC standard – a review of history, development, and standardization. *Electron. J. Inform. Technol. Constr.* 17, 134–161.
- Lee, G., Park, H.K., Won, J., 2012a. D3 City project—economic impact of BIM-assisted design validation. *Autom. Constr.* 22, 577–586.
- Lee, J.K., Eastman, C.M., Lee, J., Kannala, M., Jeong, Y.S., 2010. Computing walking distances within buildings using the universal circulation network. *Environ. Plann. B: Plann. Des.* 37, 628–645.
- Lee, J.M., 2010. Automated Checking of Building Requirements on Circulation Over a Range of Design Phases. PhD Thesis, Georgia Institute of Technology.
- Lee, S.-I., Bae, J.-S., Cho, Y.S., 2012b. Efficiency analysis of Set-based Design with structural building information modeling (S-BIM) on high-rise building structures. *Autom. Constr.* 23, 20–32.
- Li, H., Chan, G., Skitmore, M., 2013. Integrating real time positioning systems to improve blind lifting and loading crane operations. *Constr. Manage. Econom.* 31, 596–605.
- Liu, G., Shen, Q., Li, H., Shen, L., 2004. Factors constraining the development of professional project management in China's construction industry. *Int. J. Project Manage.* 22, 203–211.
- Liu, W.P., Guo, H.L., Li, H., Li, Y., 2014. Using BIM to improve the design and construction of bridge projects: a case study of a long-span steel-box arch bridge project. *Int. J. Adv. Rob. Syst.* 11, 125.
- Marzouk, M., Hisham, M., 2014. Implementing earned value management using Bridge Information Modeling. *KSCSE J. Civ. Eng.* 18, 1302–1313.
- McElwee, N., 2007. At-Risk Children & Youth: Resiliency Explored. The Haworth Integrative Healing Press, NY, USA.
- McLaughlin, J., Sreenivasan, S.V., Haas, C., Liapi, K., 2004. Rapid human-assisted creation of bounding models for obstacle avoidance in construction. *Comput.-Aided Civ. Inf. Eng.* 19, 3–15.
- Miller, R., Lessard, D.R., Michaud, P., Floricel, S., 2001. *The Strategic Management of Large Engineering Projects: Shaping Institutions, Risks, and Governance*. MIT press, Massachusetts, USA.
- Motamedi, A., Hammad, A., Asen, Y., 2014. Knowledge-assisted BIM-based visual analytics for failure root cause detection in facilities management. *Autom. Constr.* 43, 73–83.
- Motawa, I., Almarshad, A., 2013. A knowledge-based BIM system for building maintenance. *Autom. Constr.* 29, 173–182.
- OSHC, 2008. Occupational Safety and Health Statistics Bulletin Issue No. 7. Labour Department, Hong Kong Special Administrative Region.
- PMI, 2004. A Guide to the Project Management Body of Knowledge: PMBOK Guide, third ed. Project Management Institute Inc., USA.
- Porwal, A., Hewage, K.N., 2013. Building Information Modeling (BIM) partnering framework for public construction projects. *Autom. Constr.* 31, 204–214.
- Qi, J., Issa, R.R.A., Hinze, J., Olbina, S., 2011. Integration of safety in design through the use of building information modeling. In: 2011 ASCE International Workshop on Computing in Civil Engineering, June 19, 2011 – June 22, 2011. American Society of Civil Engineers (ASCE), Miami, FL, United States, pp. 698–705.
- Rajabifard, A., Williamson, I., Kalantari, M., 2012. A National Infrastructure for Managing Land Information—Research Snapshot. The University of Melbourne.
- Rasdorf, W.J., Lakmazaheri, S., 1990. Logic-based approach for modeling organization of design standards. *J. Comput. Civ. Eng.* 4, 102–123.
- Sacks, R., Barak, R., 2008. Impact of three-dimensional parametric modeling of buildings on productivity in structural engineering practice. *Autom. Constr.* 17, 439–449.
- Shim, C.-S., Lee, K.-M., Kang, L.S., Hwang, J., Kim, Y., 2012. Three-dimensional information model-based bridge engineering in Korea. *Struct. Eng. Int.* 22, 8–13.
- Solihin, W., 2004. Achieving Automated Code Checking with Ease, a White Paper, novaCITYNETS Pte Ltd., Singapore.
- Steuer, J., 1992. Defining virtual reality: dimensions determining telepresence. *J. Commun.* 42, 73–93.
- Sulankivi, K., Zhang, S., Teizer, J., Eastman, C.M., Kiviniemi, M., Romo, I., Granholm, L., 2013. Utilization of BIM-based automated safety checking in construction planning. In: *Proceedings of International CIB World Building Congress 2013, Brisbane, Australia*, pp. 5–9.
- Suresh, P., Babar, A., Raj, V.V., 1996. Uncertainty in fault tree analysis: a fuzzy approach. *Fuzzy Sets Syst.* 83, 135–141.
- Tah, J., Carr, V., 2001. Knowledge-based approach to construction project risk management. *J. Comput. Civ. Eng.* 15, 170–177.
- Tam, C.M., Zeng, S.X., Deng, Z.M., 2004. Identifying elements of poor construction safety management in China. *Saf. Sci.* 42, 569–586.
- Tang, P., Anil, E., Akinci, B., Huber, D., 2011. Efficient and effective quality assessment of as-is building information models and 3D laser-scanned data. In: *Proceedings of the ASCE International Workshop on Computing in Civil Engineering*, 19–22 June 2011, Miami, Florida, United States. *Computing in Civil Engineering*, pp. 486–493.
- Teizer, J., 2008. 3D range imaging camera sensing for active safety in construction. *ITcon* 13, 103–117.
- Teizer, J., Allread, B.S., Fullerton, C.E., Hinze, J., 2010. Autonomous pro-active real-time construction worker and equipment operator proximity safety alert system. *Autom. Constr.* 19, 630–640.
- Teizer, J., Caldas, C.H., Haas, C.T., 2007. Real-time three-dimensional occupancy grid modeling for the detection and tracking of construction resources. *J. Constr. Eng. Manage.* 133, 880–888.
- Teizer, J., Cheng, T., Fang, Y., 2013. Location tracking and data visualization technology to advance construction ironworkers' education and training in safety and productivity. *Autom. Constr.* 35, 53–68.
- Tomek, A., Matějka, P., 2014. The impact of BIM on risk management as an argument for its implementation in a construction company. *Proc. Eng.* 85, 501–509.
- Volk, R., Stengel, J., Schultmann, F., 2014. Building Information Modeling (BIM) for existing buildings—literature review and future needs. *Autom. Constr.* 38, 109–127.
- Vrouwenvelder, A., Holicky, B., Tanner, C., Lovegrove, D., Canisius, E., 2001. Risk assessment and risk communication in civil engineering. In: *Safety, Risk, Reliability – Trends in Engineering*. CIB Report Publication, Malta, pp. 885–890.

- Wang, B., Li, H., Rezgui, Y., Bradley, A., Ong, H.N., 2014. BIM based virtual environment for fire emergency evacuation. *Sci. World J.* 2014, 589016.
- Wardhana, K., Hadipriono, F.C., 2003. Analysis of recent bridge failures in the United States. *J. Perform. Constr. Facil.* 17, 144–150.
- Whyte, J., 2002. *Virtual Reality and the Built Environment*. Architectural Press, Oxford, UK.
- Williams, T.M., 1996. The two-dimensionality of project risk. *Int. J. Project Manage.* 14, 185–186.
- Wu, H., Tao, J., Li, X., Chi, X., Li, H., Hua, X., Yang, R., Wang, S., Chen, N., 2013. A location based service approach for collision warning systems in concrete dam construction. *Saf. Sci.* 51, 338–346.
- Yang, Q., Xu, X., 2004. Design knowledge modeling and software implementation for building code compliance checking. *Build. Environ.* 39, 689–698.
- Yi, K.-J., Langford, D., 2006. Scheduling-based risk estimation and safety planning for construction projects. *J. Constr. Eng. Manage.* 132, 626–635.
- Yu, H., 2009. *A Knowledge Based System for Construction Health and Safety Competence Assessment*. PhD Thesis, University of Wolverhampton.
- Zhang, J.P., Hu, Z.Z., 2011. BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 1. Principles and methodologies. *Autom. Constr.* 20, 155–166.
- Zhang, L., Wu, X., Skibniewski, M.J., Zhong, J., Lu, Y., 2014. Bayesian-network-based safety risk analysis in construction projects. *Rel. Eng. Syst. Saf.* 131, 29–39.
- Zhang, S.J., Teizer, J., Lee, J.K., Eastman, C.M., Venugopal, M., 2013. Building information modeling (BIM) and safety: automatic safety checking of construction models and schedules. *Autom. Constr.* 29, 183–195.
- Zhou, W., Heesom, D., Georgakis, P., Nwagboso, C., Feng, A., 2009. An interactive approach to collaborative 4D construction planning. *Electron. J. Inform. Technol. Constr.* 14, 30–47.
- Zhou, W., Whyte, J., Sacks, R., 2012. Construction safety and digital design: a review. *Autom. Constr.* 22, 102–111.
- Zou, P.X.W., Zhang, G., Wang, J., 2007. Understanding the key risks in construction projects in China. *Int. J. Project Manage.* 25, 601–614.