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Review of previous applications of innovative information technologies in construction health and safety

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Abstract: Construction industry is one of the most hazardous industries to work in. This problem is further exacerbated by the fact that safety performance improvement is stagnating. Information technologies (ITs) are however identified as one of the most promising methods of improving the performance of construction safety. The goal of this paper was therefore to present previous research in the application of innovative ITs to the field of construction health and safety (H&S), classified by their underlying technology and application, to identify research gaps, as well as to evaluate and describe the potential of their implementation into construction safety practice. To achieve the set goals, the research consisted of identifying and studying the existing research published in the leading journals in the field of construction H&S. The review identified 72 papers dealing with development or application of innovative ITs. The research had also identified several research gaps, which have a significant impact on the construction safety practice. These gaps focus on the construction phase, while neglecting earlier project phases; industry and project levels, while neglecting construction activity and task levels; building projects, while neglecting infrastructure projects and specific hazard types, while neglecting a universal approach. Focussing research effort on these gaps would benefit all construction safety stakeholders but mostly the prominent contractors and H&S professionals. Furthermore, recommendations for directing research focus on solving the identified issues are given in this paper.

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1 Introduction

1.1 Research background

Health and Safety (H&S) is an important aspect in the construction planning process. The statistics (U.S. Bureau of Labor Statistics 2015; EUROSTAT 2015) indicate that construction industry is a leader in some of the most undesirable statistical categories such as number of accidents at work and fatal accidents, both in absolute numbers and relative to the number of workers employed in the industry. Owing to this enormous loss of life, injuries and disabilities, which impact not only the immediate stakeholders but also the society as a whole, it is not surprising that H&S in the construction industry is of interest not just to practitioners and regulators but to researchers as well. H&S in the construction industry is a propulsive research field with a myriad of scientific papers and books published and research conducted to improve the health and lessen the probability of construction workers' injuries and death. A prominent section of construction safety research is the application of innovative information technologies (ITs) in order to improve levels of H&S in the construction sites.

1.2 Previous research interest in the application of IT to H&S

Perhaps, the first question that needs to be answered is what constitutes an innovative IT. This is not an easy task since something that was innovative 10 years ago might be extremely common today or what is widely used in one field of research might be completely new and unexplored

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in another research field. In the context of this research, innovative IT in construction H&S is any application of new or existing technology in a new or different way, with a goal to improve any aspect of construction health and safety.

Using innovative ITs to improve H&S is not a new occurrence in H&S-related research. Zhou et al. (2015) have identified that the first paper appeared in the late 1980s and since then a total of 63 research papers (up to 2013) dealing with innovative technology application as an intermediate solution to prevent workers from injuring themselves and/or others were published. They have also found a sharp increase in the yearly number of H&S-related publications since 2005 (shown in Figure 1), from one or two publications per year to as much as ten publications per year.

The reasons for the increase in the technology-enabled approaches in the construction safety can be found from the fact that traditional methods of analysis of accidents and causation data provide albeit valuable but general information for safety planning which cannot accurately predict when and where will an accident occur in a construction site (Zhang et al. 2013). Such an increase in number of innovative technologies in H&S and later in turn reliance on them to produce results that can have direct effect on human health might have unintended consequences. According to Weick, the use of innovative technologies can increase the potential for mistakes and accidents since (Weick 1985): "reliance on a single, uncontradicted data source can give people a feeling of omniscience, but because these data are flawed in unrecognized ways they lead to nonadaptive action". Zhou et al. (2012) agree that digital systems do not encourage the active challenging of assumptions, and checking and validating results produced by software. This presents a serious challenge to all potential applications of innovative technologies in the field of construction H&S.

1.3 Research goal

The goal of this paper was to present previous applications of innovative ITs and to identify whether there exists a literature gap of unexplored or insufficiently explored topics in the H&S literature, which might be worth focusing research efforts in order to best improve the construction H&S.

To do so, after describing the methodology in Section 2, this paper examines and describes the existing efforts in applying innovative ITs in the construction H&S research (Section 3). In Section 4, this paper presents the identified research gaps and gives recommendations on addressing them. Section 5 discusses the possibilities of implementing identified research in construction H&S practice, and Section 6 concludes this paper.

2 Methodology

The first step in any research endeavour is to review the existing literature in the field of study. Literature was gathered through search results from major academic publisher databases such as Science Direct, ASCE library, Taylor & Francis Online, Wiley and Springer, as well as a search on Google Scholar. Relevant papers were also found as references cited in the papers, which were found through searching the databases. The searches consisted of different combinations of keywords such as construction safety, construction H&S, building information

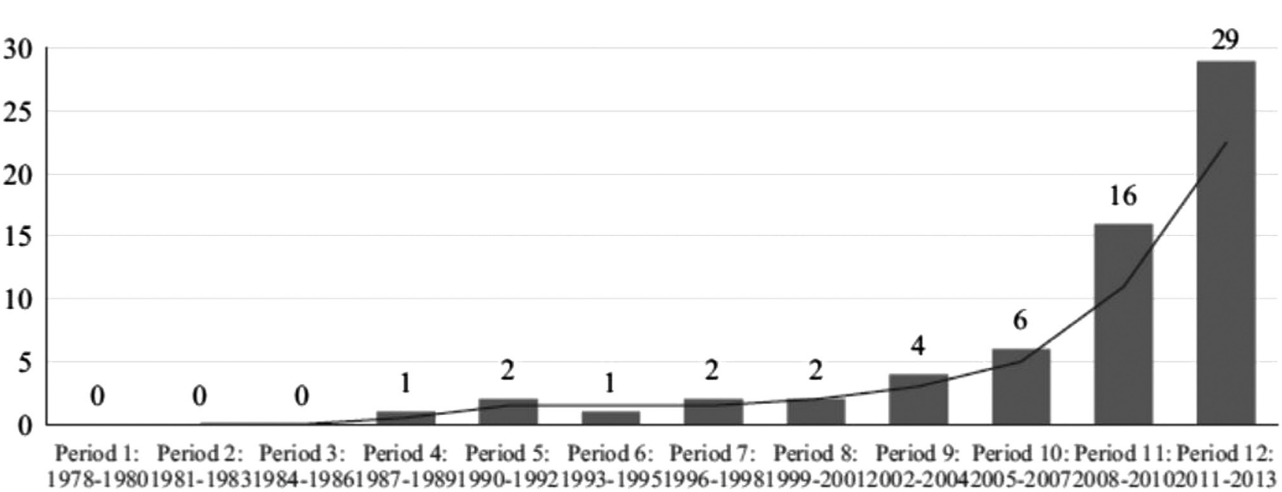

Fig. 1: The increase in the number of publications regarding application of innovative technologies in H&S (Zhou et al. 2015).

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modelling (BIM), H&S, innovative technology, IT and hazard identification. The process of data gathering was conducted from January 2018 to March 2018, and analysis was performed from March 2018 to June 2018.

Abstract and keywords of the papers displayed as search results were read and analysed, and it was determined whether the paper had an impact on the topic of the research. A total of 153 scientific papers, books and other literature sources were identified as of interest to the research topic, but only 72 of them dealt specifically with the development or application of an innovative IT in the field of construction H&S.

This paper therefore aims to present the previous research in the application of innovative ITs to the field of construction H&S, classified by their underlying technology and by application, as well as describes the potential of research's implementation in construction safety practice. This paper, in addition to presenting previous research, identifies three research gaps significant to the improvement of construction H&S and describes the means to address them.

3 Overview of previous applications of innovative ITs in construction H&S

A review of published literature has identified a myriad of potential uses for innovative technologies in the field of construction H&S. An important distinction to make is the one between the technology and its application. Technology can be seen as a platform or a tool used for a specific purpose, such as for hazard identification, safety training and rule checking, while application is the purpose that is achieved with help of technology. Previous research can therefore be divided based on these two properties: which technology it uses and what it plans to achieve. Additionally, some research combine more than one technology or have more than one application.

Some of the innovative technologies appearing in the research are BIM, four-dimensional computer-aided design (4D CAD), geographic information system (GIS), virtual reality (VR), augmented reality (AR), augmented virtuality (AV), radiofrequency identification (RFID), serious games, knowledge-based systems, database integration, checklists, prompt words, sensing technologies (laser scanning, RFID, radar, sonar, global positioning system, cameras), ontology and natural language processing (NLP). Potential applications of innovative technologies identified through the research, among others, include hazard identification, visualization, job hazard analysis (JHA), rule checking, safety training, design for safety suggestions, safety risk drivers, sensing and warning, construction planning, site safety planning and H&S issues with temporary structures.

Owing to the large number of papers dealing with innovative technologies in construction H&S, and a large number of both technology types and applications, the research papers were divided into three groups based on their level of BIM use. The three groups are:

- research with BIM as the only innovative technology
- research with BIM in conjunction with other innovative technologies
- research without BIM

Tables 1–3 contain the name of the developed tool (if applicable) and the title of the paper, which describes the tool in the first column. The second column contains information on the type of innovative technology that was used in the research, the third column lists the application of the innovative technology and the fourth column contains the reference. The tables contain all reviewed research; however, only those of a larger significance are described in more detail in the following subsections.

3.1 BIM-based innovative ITs in construction H&S

BIM is most often defined as digital representation of physical and functional characteristics of a facility (NBIMS V.3 2015). Kamardeen (2010) further states that BIM "is not just a 3D virtual model but a repository of intelligent building objects with attributes that can understand the interaction between each other, and non-geometric data about the objects and the facility for decision-makings". Although BIM models are produced using 3D modelling software (Gilkinson et al. 2015), the elements in BIM models are not just a collection of lines or polygons as they are in 2D or 3D CAD, respectively. They represent both the graphical and non-graphical aspects of a building (Eastman et al. 2008) since additional parametric information can be attributed to each of the model elements. BIM models can contain various information about the building and the building elements and actually be treated as a database (Qi et al. 2013).

Given how BIM seems to provide a solution to many of the problems faced by the construction industry and to have a large potential for application, it is not surprising that BIM is also the most often used innovative

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technology in the literature. In 25 studies (out of a total of 72 studies that describe the development of a construction H&S safety tool), BIM is the only innovative technology applied to H&S, and in 17 other studies, BIM is used either in conjunction with another innovative technology or as a foundation for that other technology (such as for VR). It also has the most unique applications. BIM is used for hazard identification, visualization, safety training, rule checking, JHA, design for safety suggestions and others. A special occurrence with BIM (and 3D/4D CAD, to a degree) is that it is not only an innovative technology by itself but also a platform for other technologies, for example, VR, AR and serious games.

As it can be seen from the "application" column of Table 1, the most prominent use of BIM in H&S is for hazard identification. Zhang et al. (2013) have used BIM to automatically detect falling hazards and model guardrails and protective covers around and over the openings in the structure. This research topic continued through the works of Sulankivi et al. (2013) who have applied the developed tool on a real-world project and Melzner et al. (2013) who implemented the same tool as an add-on to the existing BIM authoring software.

Other authors have also explored the possibilities of BIM and rule checking for identifying fall hazards. Taiebat (2011) has defined a framework for hazard identification in BIM, which supports the development of a BIM-based hazard recognition tool. His research consisted of development of a design for construction worker safety tool, which efficiently makes designs for safety suggestions available to designers and constructors.

Besides fall hazards, other hazard types identifiable in BIM are congestion hazards. Choi et al. (2014) have "suggested a framework for work-space planning process in a 4D BIM environment that integrates the characteristics of activity, workspace, and construction plan". Teo et al. (2016) have developed another hazard identification tool, called the intelligent productivity and safety system (IPASS), which allows users to analyse and monitor key aspects of the safety performance of the project before the project starts and as the project progresses.

BIM can also be used for providing designers with suggestions on how to alter their designs to make them safer to construct. One such research was presented in the papers by Qi et al. (2011, 2013) who have developed a Prevention through Design (PTD) tool that automatically checks imported BIM models and alerts users on how construction safety can be improved. Kamardeen (2010) proposed a 3D+safety model analysis approach, which would enable designers to understand the safety consequences of their design decisions by automatically detecting and flagging potential safety risks.

Temporary structures such as scaffolds, shoring, falsework, temporary stair towers and cranes all have significant impact on construction safety bur are rarely modelled in BIM. To address this issue, Kim and Cho (2015) attempted to automatically generate required temporary structures and analyse their associated safety risk. Kim and Ahn (2011) established a procedure for assessing possible hazards by visually presenting falsework objects and their locations. Their prototype is mainly focused on designing scaffolds but could be developed to include more types of temporary facilities.

A number of commercial software packages exist for leveraging potentials of BIM during the construction phase. The potential applications include using BIM for quantity take-off, scheduling, visualizing construction sequence, budgeting, logistics, resource planning and progress monitoring. Implementation of BIM during the construction phase has proven benefits in all the mentioned potential applications, so the logical step is to expand the application to include construction site safety. Most applications for including H&S in BIM are still in the research phase, either conceptual or as a prototype, and are not widely used. Existing commercial software tools, on the other hand, have only limited application in the field of construction safety.

3.2 BIM in conjunction with other innovative ITs in construction health and safety

BIM is also often used as a starting point for other innovative technologies or used in cooperation with other technologies. Table 2 lists all such research where BIM is used in combination with other technologies to improve construction H&S.

BIM can be used in combination with other technologies to enable different types of hazard identification. When used in combination with wireless sensors, BIM can be used to improve monitoring of confined spaces on construction sites. Riaz et al. (2014, 2015) have combined BIM with a wireless sensor network to remotely monitor temperature and oxygen level values. Another combination of BIM and sensors used for identifying construction hazards was developed by Kim et al. (2016) who proposed an automated hazardous area identification model based on the deviation between the optimal and actual routes. The authors hypothesize that deviation from the optimal route suggests that a hazard is present on the route and that is why the worker deviated from the calculated optimal route.

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Tab. 1: Application of building information modelling (BIM) in health and safety (H&S) research.

Title of the tool (if applicable) and title of the paper	Technology type(s)	Application(s)	Reference
Use of building information modeling in design to prevent construction worker falls	BIM	Design for safety suggestions	Qi et al. (2013)
8D BIM modelling tool for accident prevention through design	BIM	Design for safety suggestions	Kamardeen (2010)
Integration of construction worker fall safety in design through the use of building information modeling	BIM	Design for safety suggestions	Qi (2011)
Integration of safety in design through the use of building information modelling	BIM	Design for safety suggestions	Qi et al. (2011)
BIM-based planning of temporary structures for construction safety	BIM	H&S issues with temporary structures	Kim and Cho (2015)
Integrated building information model to identify possible crane instability caused by strong winds	BIM	H&S issues with temporary structures	Hasan et al. (2012)
Temporary facility planning of a construction project using BIM (building information modeling)	BIM	H&S issues with temporary structures	Kim and Ahn (2011)
Automatic design and planning of scaffolding systems using building information modeling	BIM	H&S issues with temporary structures	Kim and Teizer (2014)
Using BIM for smarter and safer scaffolding and formwork construction: a preliminary methodology	BIM	H&S issues with temporary structures	Chi et al. (2012)
Integration of safety risk factors in BIM for scaffolding construction	BIM	H&S issues with temporary structures	Collins et al. (2014)
Leveraging project models for automated identification of construction safety requirements	BIM	Hazard identification	Wang and Boukamp (2007)
Tuning up BIM for safety analysis proposing modeling logics for application of BIM in Design for Safety (DfS)	BIM	Hazard identification (fall hazards), rule checking, design for safety suggestions	Taiebat (2011)
Building information modeling (BIM) and safety: automatic safety checking of construction models and schedules	BIM	Hazard identification (fall hazards), rule checking	Zhang et al. (2013)
Utilization of BIM-based automated safety checking in construction planning	BIM	Hazard identification (fall hazards), rule checking	Sulankivi et al. (2013)
A case study on automated safety compliance checking to assist fall protection design and planning in building information models	BIM	Hazard identification (fall hazards), rule checking	Melzner et al. (2013)
Framework for work-space planning using four-dimensional BIM in construction projects	BIM	Hazard identification (workplace congestion hazards)	Choi et al. (2014)
Design for safety: theoretical framework of the safety aspect of BIM system to determine the safety index	BIM	Hazard identification, others – determining safety index	Teo et al. (2016)
BIM-based fall hazard identification and prevention in construction safety planning	BIM	Hazard identification, rule checking, fall hazards	Zhang et al. (2015b)
Classification of rules for automated BIM rule checking development	BIM	Rule checking	Solihin and Eastman (2015)
Automatic rule-based checking of building designs	BIM	Rule checking	Eastman et al. (2009)
Construction safety risk drivers: a BIM approach	BIM	Safety risk drivers, hazard identification	Malekitabar et al. (2016)
Developing a BIM-enabled bilingual safety training module for the construction industry	BIM	Safety training	Clevenger et al. (2014)
The development of a framework for a design for safety BIM tool	BIM	Safety training	Hayne et al. (2014)
A BIM-based approach for communicating and implementing a construction site safety plan	BIM	Site safety plan	Azhar and Behringer (2013)

Wang et al. (2015) have combined BIM with laser scanning and point cloud generation to identify fall and cave-in hazards. The presented method automatically identifies these two hazard types and visualizes the pit, the hazards, and the required protective safety equipment in a BIM model. Database is also one of the technologies that can be integrated with BIM for the purpose of hazard identification. In her thesis, Zhang (2014) proposes automated

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Tab. 2: Research combining building information modelling (BIM) with other innovative technologies.

Title of the tool (if applicable) and title of the paper	Technology type(s)	Application(s)	Reference
Information retrieval framework for hazard identification in construction	BIM, database	Automated information retrieval	Kim et al. (2013)
CoSMoS CoSMoS: A BIM and wireless sensor based integrated solution for worker safety in confined spaces	BIM, wireless sensors	Hazard identification (confined spaces)	Riaz et al. (2014)
Challenges in data management when monitoring confined spaces using BIM and wireless sensor technology	BIM, wireless sensors	Hazard identification (confined spaces)	Riaz et al. (2015)
Integrating safety and BIM: automated construction hazard identification and prevention	BIM, ontology	Hazard identification (fall hazards and congestion hazards), job hazard analysis (JHA), rule checking, design evaluation	Zhang (2014)
Automated hazardous area identification using laborers' actual and optimal routes	BIM, radiofrequency identification (RFID)	Hazard identification (hazards from moving through a construction site)	Kim et al. (2016)
CAVE Building safely by design	BIM, virtual reality (VR)	Hazard identification, education	Whyte et al. (2013)
Ontology-based semantic modeling of safety management knowledge	BIM, ontology	Hazard identification, JHA	Zhang et al. (2014)
Geotechnical and safety protective equipment planning using range point cloud data and rule checking in building information modeling	BIM, laser scanning, point cloud	Hazard identification, rule checking	Wang et al. (2015)
Ontology-based semantic modeling of construction safety knowledge: towards automated safety planning for job hazard analysis (JHA	BIM, ontology	JHA	Zhang et al. (2015a)
Collecting fire evacuation performance data using BIM-based immersive serious games for performance-based fire safety design	BIM, serious games	Others – collecting data related to evacuation performance	Zhang and Issa (2015)
SAVES Design and development of SAVES: a construction safety training augmented virtuality environment for hazard recognition and severity identification	BIM, augmented virtuality (AV)	Safety training	Chen et al. (2013)
SAVES SAVES: an augmented virtuality strategy for training construction hazard recognition	BIM, AV	Safety training	Chen et al. (2014)
Construction safety training using immersive virtual reality	BIM, VR	Safety training	Sacks et al. (2013)
A BIM-RFID unsafe on-site behavior warning system	BIM, RFID	Sensing and warning	Guo et al. (2014)
A framework for construction safety management and visualization system	BIM, augmented reality (AR), Game technologies	Visualization, education	Park and Kim (2013)
CAVE Hazard recognition and risk perception in construction	VR, BIM	Visualization, others – hazard identification testing	Perlman et al. (2014)
Safety by design: dialogues between designers builders using virtual reality	VR, BIM	Visualization, others – testing collaboration potential	Sacks et al. (2015)

identification of two hazard types, fall hazards and congestion hazards. The first type is fall hazards, which were already discussed in the previous section. The second type is congestion hazards. The research proposes using Global Positioning System (GPS) to gather location data of workers conducting activities on different element types to determine the workspace's shape and size for each of the activity for each building element. Knowing what area the workers occupy while conducting their activities can be used to model occupancy of the construction site. Connecting this information to the construction schedule can provide temporal and spatial locations of workers, which could be used to identify workplace congestion.

BIM can also be used to identify hazards through JHA. Two such sets of research were discovered whose goal was to identify hazards faced by workers on the construction

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site by integrating BIM/3D CAD with a database. Given that performing JHA is generally time consuming and labour intensive and that the construction schedule often changes, Zhang has developed an application to automate the JHA process by integrating the JHA database with BIM models (Zhang 2014, Zhang et al. 2015a). This was achieved by developing the construction safety ontology whose purpose was not only to formalize current construction safety knowledge but also to support hazard identification and mitigation through BIM.

The second set of research, the construction hazard assessment with spatial and temporal exposure (CHASTE), has adopted a different conceptual approach to overcome the problems of hazard identification in construction. It is a conceptual model that enables forecasting safety risks at appropriate levels of detail and reliability in construction or in any other project-based production system with dynamic environments (Rozenfeld et al. 2009). The fundamental difference is that accidents are replaced with loss-of-control events and the potential for any worker to be exposed by them (Rozenfeld et al. 2010). Another difference from earlier research is that CHASTE explicitly accounts for the fact that construction workers are frequently endangered by workers performing other activities (Rozenfeld et al. 2009).

BIM can also be used as a foundation for other technologies: for producing 3D building models, which are then used in VR, AR, AV, or in serious game technologies. These technologies are used mostly for safety training and for visualizing construction sequence.

Safety training in general aims to improve the capability of hazard recognition. To this end, Chen et al. (2014) have developed the system for augmented virtuality environment safety (SAVES). SAVES is an application that integrates BIM models with 2D images to interactively train construction workers on hazard identification and safe working procedures (Chen et al. 2013).

Another innovative technology used for safety training is VR. Sacks et al. (2013) define VR as "a technology that uses computers, software and peripheral hardware to generate a simulated environment for its user". They also tested the hypothesis that safety training using innovative methods (in their case VR) would be feasible, more effective and would result in higher recall in identifying and assessing construction safety risks than equivalent training using conventional safety training methods.

Safety training can also be conducted through the use of serious games. Zhang and Issa (2015) define serious games as video games that are focused on supporting activities such as education, training, health, advertising, or social change. They proposed a method for gathering behaviour of players in an emergency evacuation scenario. Lin et al. (2011) have also used serious games for safety education. Their game, safety inspector, aims to provide a comprehensive safety training environment in which students assume the roles of safety inspectors and walk through the virtual construction site to identify potential hazards.

3.3 Other innovative ITs in construction H&S

Previous two subsections have described research in H&S, which includes the use of BIM. There are of course other innovative technologies that among others include 4D CAD, GIS, databases and knowledge-based systems. A full list of innovative technologies' H&S-related research identified in this literature review is given in Table 3.

Technologies other than BIM can also be used for hazard identification. A technology conceptually similar to BIM but focused on the surroundings of the building element is GIS. An example of using GIS for hazard identification is presented in a paper by Bansal (2011). In the paper, he discusses "the use of GIS in the development of safety database from which safety information are retrieved and linked with the activities of the schedule or components of a building model". The motivation of including GIS in H&S research lies in the fact that BIM and 4D CAD cannot include all factors that influence construction safety. He therefore proposes that including geospatial analysis capabilities of GIS on a single platform with a 3D model and 4D scheduling may help in effective safety planning process.

Another technology used for hazard identification, which is even more similar to BIM, is 4D CAD. Both include 3D visual representations of building elements, and construction schedules can be connected with model elements in both technology types, but elements in 4D CAD lack additional parametric information. Mallasi (2006) has used 4D CAD to identify and minimize workspace congestion between construction activities' execution space. In his research, he developed a methodology and a tool to assist planners with the assignment of activities' execution space, as well as identification and visualization of workspace congestion.

Benjaoran and Bhokha (2010) have also used 4D CAD as a starting technology, and they developed a rule-based system that analyses design information to automatically detect falling hazards and to indicate necessary safety measures. This research, unlike other fall hazard-related research, does not use BIM but rather 4D CAD. The model elements are traditional 3D objects combined with a

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Tab. 3: H&S research in innovative technologies that does not include BIM.

Title of the tool (if applicable) and title of the paper	Technology type(s)	Application(s)	Reference
Automated content analysis for construction safety: a natural language processing system to extract precursors and outcomes from unstructured injury reports	Natural language processing	Data extraction and structuring	Tixier et al. (2016)
Safety hazard identification on construction projects	Database	Decision support system	Carter and Smith (2006)
Computer-aided DSS for safety monitoring of geotechnical construction	Geographic information system (GIS)	Decision support system	Cheng et al. (2002)
OHS Log Integrated safety in design	Conceptual framework	Design for safety suggestions	Schultz and Jørgensen (2014)
Design for construction safety toolbox Tool to design for construction worker safety	Database	Design for safety suggestions	Gambatese et al. (1997)
ToolSHeD™: the development and evaluation of a decision support tool for health and safety in construction design	Knowledge-based system	Design for safety suggestions	Cooke et al. (2008)
The development of a knowledge-based system to deliver health and safety information to designers in the construction industry	Knowledge-based system	Design for safety suggestions	NNC Limited (2003)
MAARD Prevention guide for designers based on analysis of about 2000 accidents	Management model	Design for safety suggestions	Soeiro et al. (2014)
Integrative model for quantitative evaluation of safety on construction sites with tower cranes	Model for quantitative evaluation of safety levels	H&S issues with temporary structures	Shapira et al. (2012)
Application of 4D visualization technology for safety management in metro construction	Four-dimensional computer-aided design (4D CAD)	Hazard identification	Zhou et al. (2013)
ASPP Automated safety planning approach for residential construction sites in Malaysia	Database	Hazard identification	Zolfagharian et al. (2014)
Application of geographic information systems in construction safety planning	GIS, database	Hazard identification	Bansal (2011)
PECASO Dynamic quantification and analysis of the construction workspace congestion utilizing 4D visualization	4D CAD	Hazard identification (work-place congestion hazards)	Mallasi (2006)
CHAIR Safety in design tool	Prompt words	Hazard identification, design for safety suggestions	Workcover (2011)
CHASTE Construction job safety analysis	Database	Hazard identification, job hazard analysis	Rozenfeld et al. (2010)
CHASTE 'CHASTE': construction hazard assessment with spatial and temporal exposure	Database	Hazard identification, job hazard analysis	Rozenfeld et al. (2009)
CHASTE Spatial and temporal exposure to safety hazards in construction	Database	Hazard identification, job hazard analysis	Sacks et al. (2009)
Activity-based safety risk quantification for concrete formwork construction	Risk assessment software	Hazard identification, risk classification	Hallowell and Gambatese (2009)
Design-for-safety-process tool Capturing safety knowledge using design-for-safety-process tool	Knowledge-based system	Hazard identification, safety training	Hadikusumo and Rowlinson (2004)
Design-for-safety-process tool Integration of virtually real construction model and design-for-safety-process database	Knowledge-based system	Hazard identification, safety training	Hadikusumo and Rowlinson (2002)
VP-based safety management in large-scale construction projects: a conceptual framework	Virtual prototyping	Hazard identification, safety training	Guo et al. (2013)
CVP The use of virtual prototyping for hazard identification in the early design stage	Virtual reality (VR), 4D CAD	Hazard identification, visual-ization	Chan King et al. (2012)

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Tab. 3: Continued.

Title of the tool (if applicable) and title of the paper	Technology type(s)	Application(s)	Reference
CHSM CSHM: web-based safety and health monitoring system for construction management	Web-based system	Monitoring and assessing construction health and safety (H&S) performance	Cheung et al. (2004)
Heat map generation for predictive safety planning: preventing struck-by and near miss interactions between workers-on-foot and construction equipment	Hazard index heat map	Preventing struck-by hazards	Golovina et al. (2016)
Risk assessor model Risk assessment in construction	Risk assessment software	Quantifying safety risk for activities	Jannadi and Almishari (2003)
SliDeRulE Quantification and assessment of safety risk in the design of multistory buildings	Online tool	Quantifying safety risk for building elements	Dharmapalan et al. (2014)
Safety planning and control model Safety and production: an integrated planning and control model	Safety management tool	Safety planning	Saurin et al. (2004)
A pilot study of a 3D game environment for construction safety education	Serious games	Safety training	Lin et al. (2011)
Predicting movements of onsite workers and mobile equipment for enhancing construction site safety	Sensing technologies (cameras)	Sensing and warning	Zhu et al. (2016)
Autonomous pro-active real-time construction worker and equipment operator proximity safety alert system	Sensing technologies (radiofrequency identification [RFID])	Sensing and warning	Teizer et al. (2010)
Recommendations for evaluating & implementing proximity warning systems on surface mining equipment	Sensing technologies (RFID, radar, sonar, infrared, sonar, cameras)	Sensing and warning	Ruff (2007)

construction schedule. A paper by Chan King et al. (2012) also describes a tool that utilizes 4D CAD for hazard identification. They have developed a multidimensional simulation tool called construction virtual prototyping (CVP). This tool utilizes 3D models and simulation of worker behaviour to model and visualize the construction process, thus allowing users to simulate construction processes in a 3D environment before construction takes place.

All research efforts previously described in this subsection have used a type of 3D model in their hazard identification process. Zolfagharian et al. (2014) have shown that 3D models are not necessary for hazard identification. Their research proposed an automated safety planning plug-in (ASPP), a plug-in for scheduling software applications whose objective is to mitigate the occurrence of construction accidents. The tool extracts construction activities from computer-based schedules, integrates construction schedules with construction safety databases (construction safety hazard database, risk assessment database and safety measure database) and identifies risk levels, safety regulations and hazards related to each of the activities.

A subset of hazard identification research is the sensing and warning technologies. In essence, their goal is to eliminate collision hazards and identify them before they occur. There are several different types of technologies used for identifying collision hazards. They include RFID, GPS, radar systems, sonar systems, cameras and infrared cameras. Although a large number of technologies are available, the industry is still reluctant to implement proximity warning systems due to a lack of field testing and research to determine the effectiveness of the systems, poor reliability due to possibly high false alarm rates and poor reliability and high maintenance requirements due to the harsh environment (Ruff 2007).

Teizer et al. (2010) have presented the development of such a sensing and warning system in their paper. The objective of their research was to increase situational awareness and safety in construction activities, which include construction machinery by utilizing an autonomous wireless proactive real-time warning device. The technology alerts both workers and equipment operators when the proximity between the antenna (installed on the equipment) and the receiver (carried by workers) gets too close.

A conceptually different method is presented by Zhu et al. (2016). Their research proposed the use of Kalman filters to predict movements of workers and mobile equipment on construction sites using multiple cameras as input. An advantage of this method is that it does not require installing remote sensors on either equipment or

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workers, which incurs additional costs and in some cases is impossible since the equipment cannot be physically tagged.

Some technologies integrate more than one application. One of such combinations is the use of innovative technologies for hazard identification and safety training. This combination is expected, since safety training most often includes training construction site workers to identify hazards.

Hadikusumo and Rowlinson (2002, 2004) have developed a design-for-safety-process (DFSP) tool. The tool aims to accomplish three tasks: capture safety knowledge from safety engineers, assist safety engineers in identifying construction hazards and train students and inexperienced safety engineers (Hadikusumo and Rowlinson 2004). DFSP tool is therefore first used as an innovative method to capture the knowledge of safety engineers in identifying safety hazards at construction sites and accident precautions. The captured knowledge is then entered in the DFSP database, which is one of the three components of the tool, the other two being virtually real construction model and VR functions (Hadikusumo and Rowlinson 2002). Integration of these components helps to identify safety hazards that are produced at the design stage by enabling the user to do a walk-through in the virtually real project. The DFSP tool can also list possible hazards and accident precautions for selected model component (Hadikusumo and Rowlinson 2002).

Virtual prototyping (VP) is another technology that can be used in hazard identification and safety training. Guo et al. (2013) define VP as a "computer aided design and manufacturing process with construction of digital product models (virtual prototypes) and realistic graphical simulations." They have developed a conceptual framework of adopting VP technology to aid in construction safety management. The framework consists of three components: modelling and simulation, identification of unsafe factors and safety training. A real-life case study presented in the paper demonstrated that VP can provide a virtual experimentation platform for identifying safety problems in construction processes (Guo et al. 2013).

3.4 Overview and summary of the research

Following the presentation of previous research into innovative ITs in construction H&S, this subsection contains a summary of the research based on the number of appearances of each of the innovative technologies, each of the applications and the number of papers per journal or conference.

It is not surprising that the most often cited technology is BIM, which has 41 occurrences. It is followed by the database, which however has only eight occurrences. The third most represented technology is AR (five occurrences), closely followed by RFID, knowledge-based systems, 4D CAD and sensing technologies, all of which have four occurrences. Furthermore, ontology and wireless sensors have three occurrences, while wireless sensors, AV, GIS, risk assessment software, online tools and safety management tools have two occurrences each. All remaining technologies (laser scanning, NLP, conceptual framework, management model, model for quantitative evaluation of safety levels, prompt words, virtual prototyping, web-based system and hazard index heat map) appear only once in the literature review. All the technologies with more than one occurrence are shown in Figure 2.

Similar disproportion of the number of applications is evident in the numbers of occurrence for each of the applications, which is presented in Figure 3. Hazard identification is not surprisingly the most often found technology in the literature review (30 occurrences), due

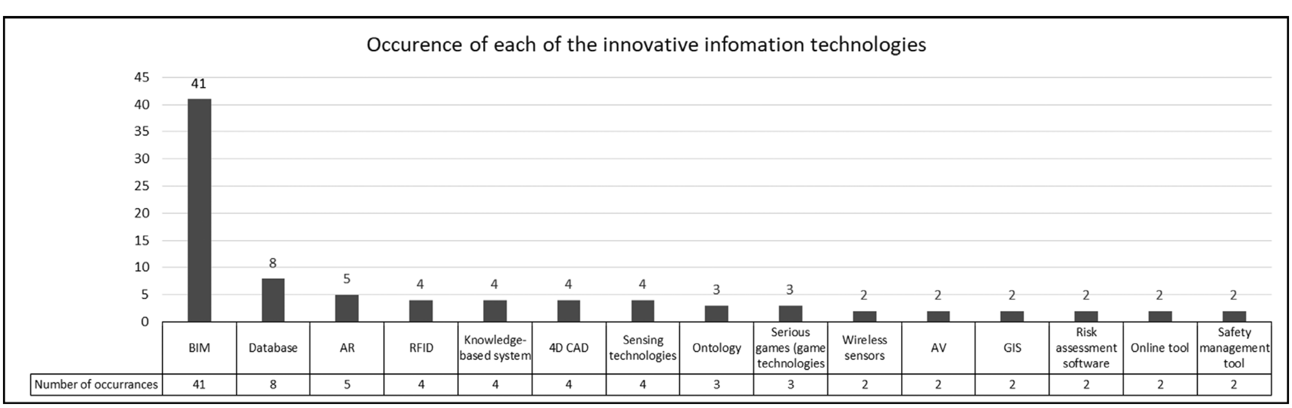

Fig. 2: Occurrence of each of the innovative information technologies.

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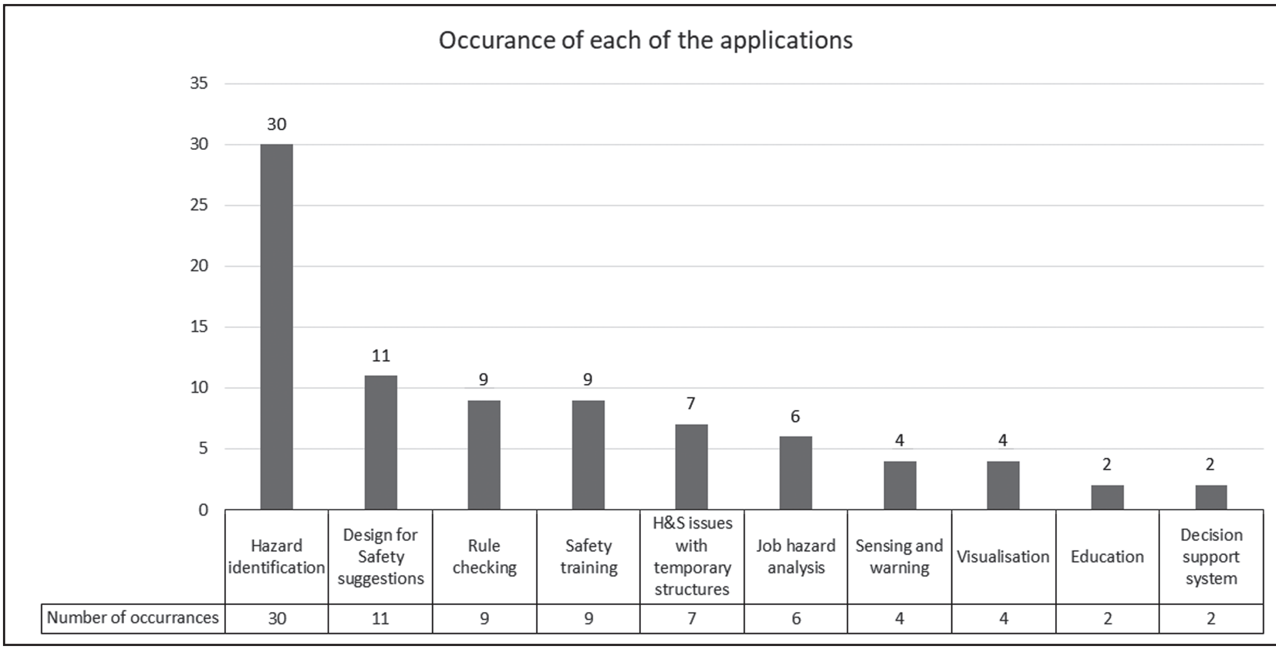

Fig. 3: Occurrence of each of the applications.

to the importance of the issue and due to a specific search parameter, which among others included hazard identification. The second most represented application is design for safety suggestions (11), followed by rule checking and safety training (both with nine occurrences). The remaining applications with a significant number of occurrences are H&S issues with temporary structures (seven), JHA (six), sensing and warning (four), visualization (four), education (two) and decision support system (two). The remaining applications are only featured once in the reviewed literature. These applications include determining safety index, safety risk drivers, automated information retrieval, design evaluation, collecting data related to evacuation performance, data extraction and structuring, risk classification, monitoring and assessing construction H&S performance, preventing struck-by hazards, quantifying safety risk for activities, quantifying safety risk for building elements and safety planning.

Finally, it might be interesting to see which journal or conference proceedings contained the most papers that describe the use of innovative ITs in the field of construction H&S. Most represented journal is *Automation in Construction* with 17 papers, followed by the *Journal of Construction Engineering and Management* (eight papers) and Computing in Civil Engineering conference (seven papers). Additionally, the review process identified three papers in *Safety Science* and two papers each in *Journal of Computing in Civil Engineering* and Computing in Civil and Building Engineering. A total of 21 journals or conferences appeared only once in the reviewed literature. All journals and conferences that featured more than once are presented in Figure 4.

4 Identified research gaps and recommendations for addressing the gaps

Zhou et al. (2015) have identified several research gaps in their literature review paper. These research are 90% focused on the construction phase neglecting the design and preconstruction phases; more than 80% of them are focused on the industry and project levels, neglecting construction activity and task levels and 205 out of 234 papers are focused on building projects, neglecting infrastructure projects.

During the course of this research, it was discovered that in the years following the research of Zhou et al, a larger number of studies emerged that dealt with construction H&S in the design and preconstruction phases, specifically the research focused on concepts such as design for safety and prevention through design. Additionally, although a significant number of papers are still focused on the industry and project levels, a larger percentage of papers deal with the activity and task levels of the construction process.

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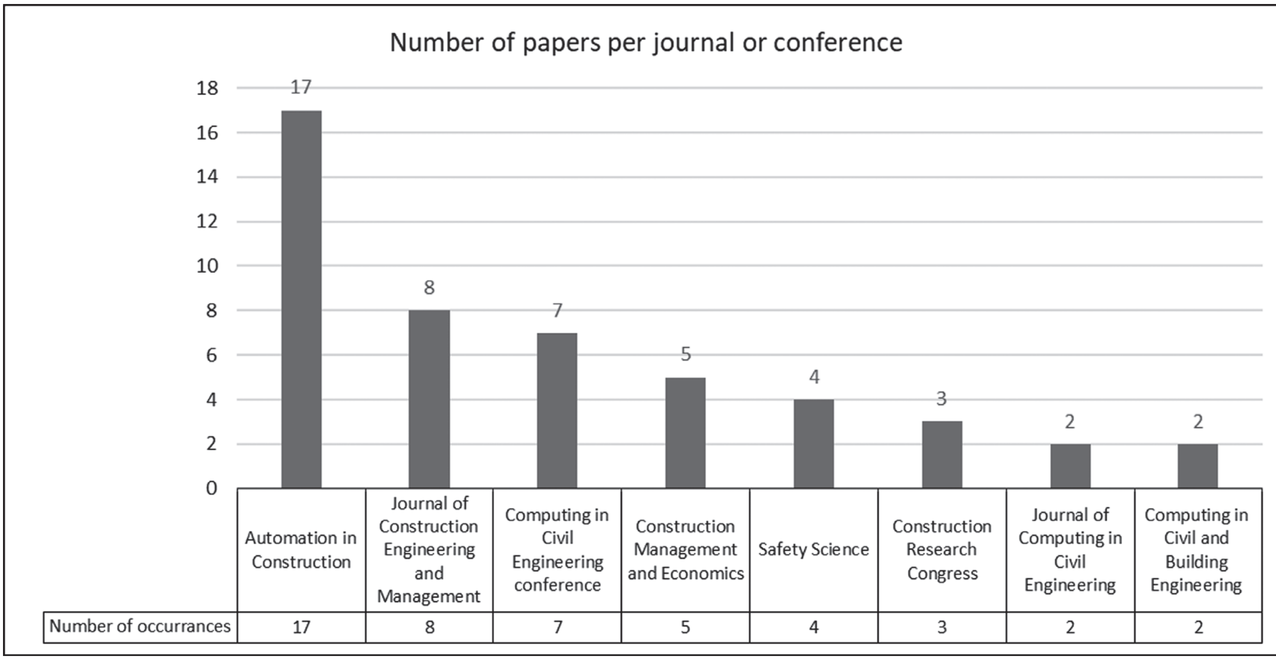

Fig. 4: Number of papers per journal or conference.

What still remained as a research gap was an overemphasis on building projects and a lack of a unified approach towards hazard identification. As can be seen from the research presented in Tables 1–3, most of the research focuses on one or at most three hazards types such as fall hazards, collision hazards, congestion hazards and hazards related to temporary structures.

The most efficient way of addressing this issue would be to develop a conceptually universal hazard identification methodology that would be applicable to all project types and useful in all project phases. Construction safety ontology research by Zhang et al. (2015a) and Rozenfeld et al. (2009) with the CHASTE method have started in this direction by proposing ways of automated hazard identification. Mihić et al. (2018) builds upon these previous research by proposing a conceptually universal hazard identification methodology along with a construction hazard database, which could be used to identify any construction hazard as long as it results directly from construction of a building element.

5 Potential of implementing innovative ITs in construction safety practice

All construction H&S stakeholders could stand to benefit from implementing innovative ITs in construction safety practice, but mostly H&S coordinators are tasked with ensuring that construction work is carried out in the safest possible way. One of their responsibilities is creating a site safety plan that has strictly prescribed components. These are all listed in the ordinance on H&S in temporary and mobile construction sites (2008). Most of the practitioners view these site safety plans as an administrative form that needs to be created to satisfy the prescribed requirements so that they do not get fined if an inspection happens at the construction site. For this reason, the site safety plans are overly detailed and extremely similar to each other. Site safety plan for a small house does not differ much in contents and details from a site safety plan for a large infrastructure project. Only some specific details are changed on a plan-to-plan basis. They are not tailored to each individual construction site as is intended by the EU directive on the implementation of minimum safety and health requirements in temporary or mobile construction sites (92/57/EEC, 1992).

The other side of the problem is that H&S coordinators do not have the time or the resources to conduct such detailed analysis of each construction site. This is where BIM could at least mitigate this problem by automating certain aspects of creating site safety plans. The research presented in a PhD thesis by Mihić (2018) proposes a system that identifies possible construction hazards from BIM model elements. It also takes into consideration the interaction from different activities and general construction hazards, which H&S

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coordinators are also required to identify. The presented research is however only focused on hazard identification, and site safety plans need to contain a lot of other information.

Other requirements could however also be created in BIM or extracted from BIM models. These include construction site layout, incorporating existing installations (electrical, plumbing, sewage, etc.), defining unloading and storage areas, determining the construction site boundary, determining traffic routes and evacuation routes, determining especially dangerous areas on the construction site, etc.

Some public standards on integrating BIM with H&S practice already exist, such as publicly available specifications (PAS) 1192-6:2018 "Specification for collaborative sharing and use of structured health and safety information using BIM" (British Standards Institution, 2018b). Construction industry stakeholders (BIM users) "have been slow to collaborate on sharing structured health and safety (H&S) information across project and asset lifecycles"; therefore, the PAS aims to provide the guidelines on "how H&S information is produced, flows and can be used throughout the project and asset lifecycle" (British Standards Institution, 2018a). The standard presents a step in the positive direction for adoption of BIM in the field of construction H&S.

6 Conclusion

This paper presents the literature review of existing studies involved in the application of innovative ITs to improve construction H&S. A total of 72 research papers were identified as relevant to the research and studied in further detail, all of which are listed in Tables 1–3. For all of these papers, the technology (or technologies) developed or used in the research, the application(s) of said technologies and the references were identified and presented in the tables. Owing to the relatively large number of papers, for presentation clarity, they were divided into three groups based on their level of BIM use. Besides being listed in the tables, papers of more significance to the research were expanded upon in their respective subsections with a short overview of what was achieved through the research.

The research presented in this paper has found several important research gaps:

- focus on the construction phase, while neglecting earlier project phases;
- focus on the industry and project levels, while neglecting construction activity and task levels;
- focus on building projects, while neglecting infrastructure projects and
- focus on one or at most three hazard types, while neglecting an integrated approach.

Although after the research of Zhou et al, more papers dealing with activity and task levels, and design and preconstruction phases have emerged, the overwhelming focus still remains on buildings as a project type. Furthermore, most of the research is either in the conceptual phase or focuses only on one or two specific aspects of construction H&S. To address this issue, this paper recommends developing a more universal approach to hazard identification, along with continuing the existing research efforts.

An additional result of this paper is a summary of the identified research. This paper identified the most often used technology and application, as well as the journal with the most papers dealing with innovative technologies in construction H&S. Potentials for implementing innovative technologies (specifically BIM) in construction safety practice and existing standards are also discussed in this paper.

Results presented in this paper could be of use to researchers to aid them in choosing specific research focus as well as to practitioners who would benefit from the results of the conducted research. Future research should, therefore, be focused on addressing the existing gaps in order to discover additional ways to improve the levels of H&S in the construction industry.

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