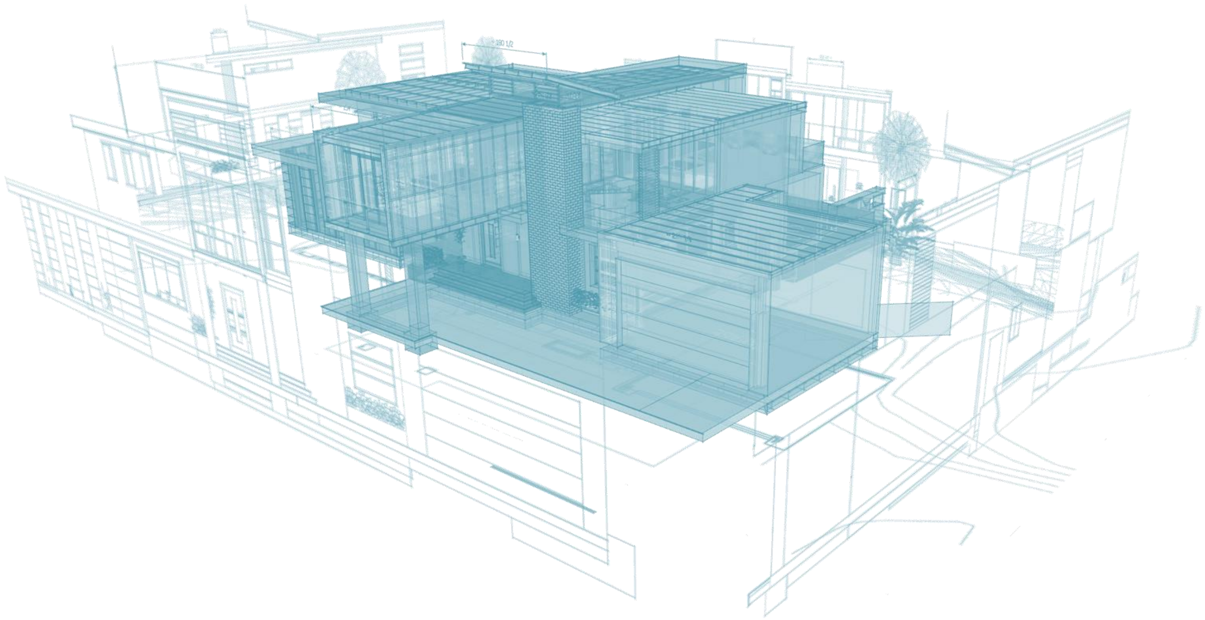

Applications of Building Information Modelling to Construction Health and Safety: A Systematic Review

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Executive summary

Background: This systematic literature review was conducted for the BIMSafe NZ project, which is a three-year, $1.7 million partnership between the construction industry and the government that intends to lower New Zealand's accident and injury rates by improving risk understanding, communication, and mitigation.

Objectives: The literature review aims to understand the current status of BIM applications for construction health and safety and identify BIM-based health and safety best practices in the project lifecycle (i.e., design, procurement, and construction). It covers academic publications, related BIM standards, industry best practices, and case studies. In specific, this review study focuses on the following main aspects:

- BIM and BIM-related technologies for safety in design (SiD) and site construction health and safety management,
- Integrating BIM and health and safety into procurement processes,
- BIM information flow and management for whole lifecycle health and safety management,
- Drivers and barriers to the implementation of BIM for construction health and safety management,
- Existing standards, guidelines, and best practices of BIM-based health and safety.

Methods: A systematic review method was adopted to identify and analyse relevant academic articles, BIM for safety standards, guidelines, best practices, and industry case studies. The method consists of five main steps: literature search, selection, coding, data analysis, and discussion.

BIM-based safety in design: Previous research efforts were focused on developing BIM-based rule checking and risk assessment systems. Several knowledge bases have been developed to support rule-based reasoning and risk assessment processes. In these research efforts, BIM is mainly used as a database, and visualization platform from which objects and their attributes were extracted as inputs for reasoning and assessment, and outputs (e.g., hazards and control measures) are displayed to facilitate communication. Despite these advancements, there is a strong need to develop a comprehensive knowledge base that enables identifying most of, if not all, hazards, especially those caused by the spatial and temporal relationships among building elements and construction activities. Second, how these techniques work through different design phases (i.e., concept, developed, and detailed design) needs to be investigated.

BIM-based health and safety in procurement: There is minimal research investigating BIM-based health and safety during the procurement stage. Nevertheless, BIM4H&S Working Group developed a Project Information Requirements (PIR) template to help the client specify health and safety information requirements in a BIM project. These requirements were set up based on the PAS 1192-6 and classified into three types: functional, role and process, and information cycle requirements.

BIM-based site health and safety management: Significant research achievements have been made in several aspects of BIM-based site health and safety management, including hazard management, risk assessment, site safety inspection and monitoring, temporary structure, heavy equipment, safety training and education, and work space planning.

Future research directions: This report recommends six specific future research directions:

- Develop safety object libraries
- Develop a comprehensive computable safety knowledge base
- Standardize health and safety information structure
- Evaluate the performance of BIM-based health and safety applications by accident reduction
- Investigate BIM-based multi-stakeholder collaboration on health and safety
- Integrate health and safety into the NZ BIM Handbook

1 Introduction

1.1 Construction health and safety

From a global perspective, the construction industry suffers poor safety performance. It remains one of the most dangerous workplaces and the top contributors to workplace injuries in many countries (e.g., USA, UK, Australia, China, and New Zealand) (Pinto et al., 2011; Shin et al., 2014; Waehrer et al., 2007; Zhou et al., 2015). For example, according to Stats NZ, the New Zealand construction industry has remained the second-highest among other industries from 2009 and 2018 (see Figure 1). However, it was slightly lower than the manufacturing industry in 2019. In addition, the industry has had an alarming increase in the number of claims for work-related injuries since 2011, as shown in Figure 2.

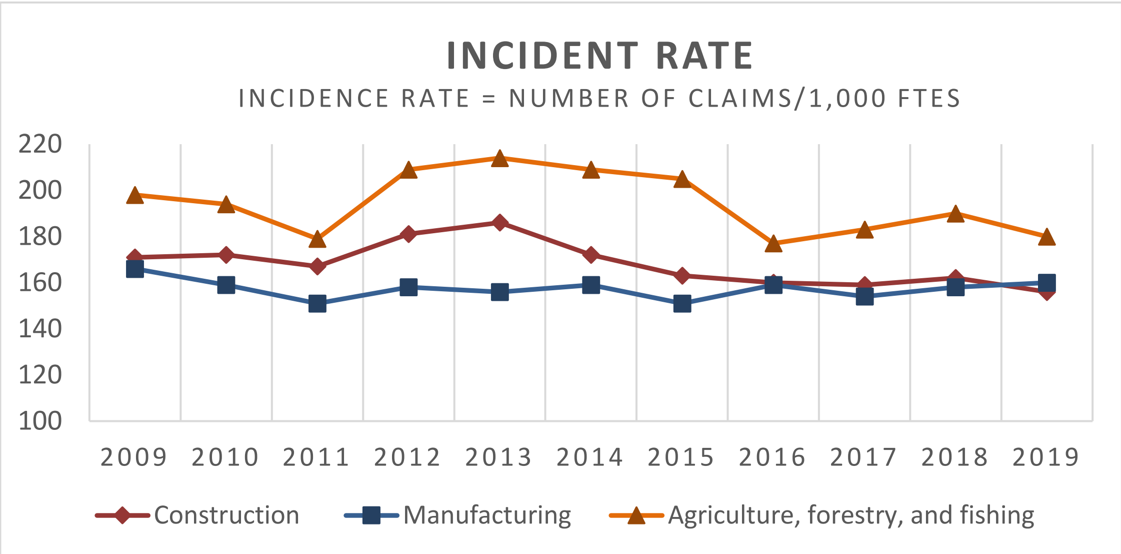

Figure 1 Incident rate of construction, manufacturing, and agriculture, forestry, and fishing

Note: Incidence rate = number of claims/1,000 FTEs. The number of full-time equivalent employees (FTEs) is estimated by the Household Labour Force Survey (HLFS) for the relevant year.

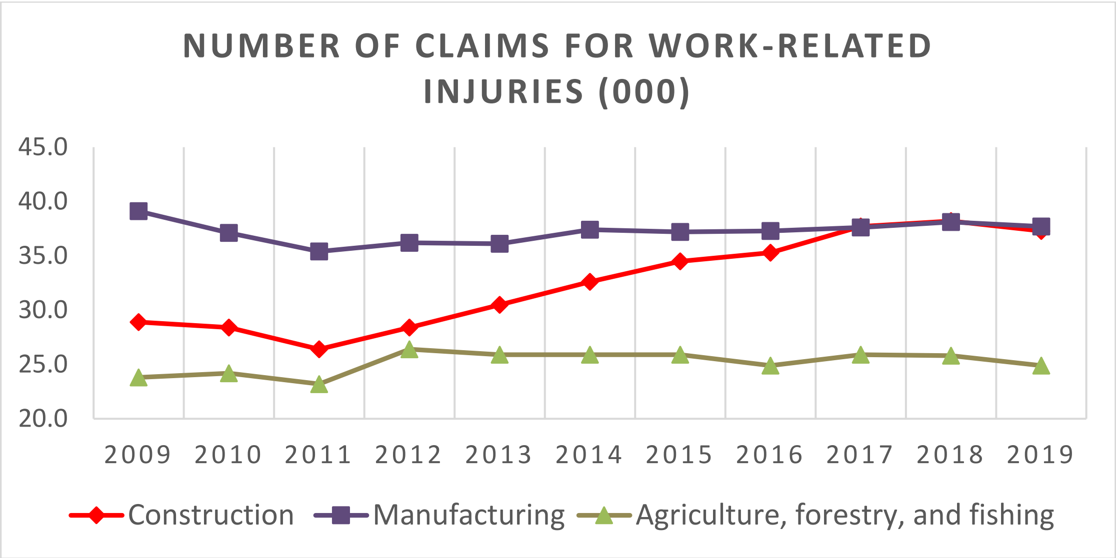

Figure 2 Number of injury claims

Managing construction health and safety involves several unique challenges, such as different trades, multi-organizational project structure, constantly changing work environment, and transient workforce (Guo et al., 2015; Rowlinson, 2004). Although technologies have been increasingly implemented in construction projects, the industry is still labour intensive, dominated by a large proportion of small businesses with relatively low capacity and capability to manage health and safety. In addition, multiple stakeholders (e.g., regulators, unions, clients, main contractors, subcontractors and workers) along the whole project cycle play various roles in contributing to site safety, which causes coordination problems. Partly due to these challenges, accidents and injuries still occur repeatedly on sites, and it appears that construction safety has reached a plateau.

1.2 BIM for health and safety

Safety has experienced an evolution of four "ages of safety" (i.e., a technical age, a human factor age, a management systems age, an adaptive age) (Borys et al., 2009; Reiman & Oedewald, 2009). Over the last two decades have seen increasing applications of BIM to construction health and safety. BIM is defined as "*a modelling technology and associated set of processes to produce, communicate, and analyze building models*" (Sacks et al., 2018). BIM is seen as a game-changing technology and method to address the construction industry's long-lasting issues, such as delay, cost overrun, and poor quality. As a lifecycle platform, BIM has proven benefits to almost all stakeholders in each project phase, from concept, design, and construction to facility management. It can increase building performance and quality, improve collaboration among project team members, help contractors quickly respond to design changes, synchronize design and construction planning, and integrate facility operation and management systems

(Sacks et al., 2018).

BIM is becoming mainstream in the construction industry. As surveyed by (EBOSS, 2021), BIM saturation has increased markedly in New Zealand, from 34% to 70%. Recent years have seen increasing research on integrating health and safety into BIM. Traditional construction health and safety management is mainly manual and paper-based. BIM has the potential to digitalize health and safety information, facilitate risk assessment and communication, and support decision making. As a rich database, it enables advanced big data and artificial intelligence techniques to generate new knowledge.

1.3 Research objectives of the literature review

The literature review aims to understand the current status of BIM applications to construction health and safety and identify BIM-based health and safety best practices in the project lifecycle (i.e., design, procurement, and construction). This review study differs from other published BIM-based construction health and safety review studies. It covers academic publications and related BIM standards, industry best practices, and case studies. In specific, this review study focuses on the following main aspects:

- BIM and BIM-related technologies for safety in design (SiD) and site construction health and safety management
- Integrating BIM and health and safety into procurement processes
- BIM information flow and management for whole lifecycle health and safety management
- Drivers and barriers to the implementation of BIM for construction health and safety management
- Existing standards, guidelines, and best practices of BIM-based health and safety.

2 Methods

A systematic review method (Guo et al., 2017) was adopted to identify and analyse relevant academic articles, BIM for safety standards, guidelines, best practices, and industry case studies. The method consists of five main steps: literature search, selection, coding, data analysis, and discussion. BIM-related standards, legislation, regulations, global industry reports, and case studies will be collected manually for further analysis.

2.1 Literature search

Scopus was selected for literature search due to its comprehensive coverage of relevant peer-refereed academic papers (Patel et al., 2021). Research areas were classified according to the BIM applications to health and safety in different phases of a construction project, such as design, procurement, and construction. Maintenance safety during the operation stage is beyond the scope of this review study. The time frame of the review is from 2005 to 2021. Moreover, only literature written in English were included. An initial search identified 52 papers related to BIM-based safety in design. Two rounds of the search were conducted to find papers related to BIM-based health and safety in procurement. The first round was focused on BIM-based procurement in general (185 papers identified), while the second round aimed to research papers that integrate both BIM and health and safety into procurement (8 papers identified). In "BIM for safety during construction" stage, 785 pieces of literature were identified. Table 1 demonstrates the keywords used for each search area. Google search was used to identify BIM for safety standards, guidelines, best practices, and industry case studies.

Table 1 keywords for each research area

Research area	Keywords	Search results
BIM-based safety in design	(TITLE-ABS-KEY ("Building Information Modelling") OR TITLE-ABS-KEY ("BIM") AND TITLE-ABS-KEY ("Design for Safety") OR TITLE-ABS-KEY ("DfS") OR TITLE-ABS-KEY ("Safety in Design") OR TITLE-ABS-KEY ("SiD") OR TITLE-ABS-KEY ("Safety through Design") OR TITLE-ABS-KEY ("Prevention through Design") OR TITLE-ABS-KEY ("PtD"))	52
BIM-based procurement	(TITLE-ABS-KEY ("Building Information Modelling") OR TITLE-ABS-KEY ("BIM") AND TITLE-ABS-KEY ("procurement") OR TITLE-ABS-KEY ("bid") OR TITLE-ABS-KEY ("tendering"))	185
Integrating BIM and health and safety into procurement	(TITLE-ABS-KEY ("Building Information Modelling") OR TITLE-ABS-KEY ("BIM") AND TITLE-ABS-KEY ("procurement") OR TITLE-ABS-KEY ("bid") OR TITLE-ABS-KEY ("tendering") AND TITLE-ABS-KEY ("construction") AND TITLE-ABS-KEY ("safety"))	8
BIM for Safety during construction	TITLE-ABS-KEY ("BIM" AND "Building information modeling" AND "Construction" AND "safety")	785

2.2 Selection

In the selection step, the BIM-based design for safety, BIM for Safety during procurement, and BIM for Safety during the construction stage identified 44, 1, and 492 articles. The literature was coded by a unique number for further analysis. The inclusion and exclusion criteria and the number of articles for each stage are presented in Table 2.

Table 2 Inclusion and exclusion criteria

Stage	Inclusion or exclusion	Number of articles	Reasons	Number of articles left for analysis
BIM-based design for safety	Inclusion	52	From Scopus	44
	Inclusion	4	Other source articles related to BIM-based safety in design (SiD)	
	Exclusion	2	Repeated result	
	Exclusion	10	Not related to DfS in the AEC industry	
BIM for Safety during procurement	Inclusion	185	From Scopus (Round 1 search)	1
	Inclusion	8	From Scopus (Round 2 search)	
	Exclusion	7	Repeated result	
	Exclusion	185	Not related to safety during procurement in AEC industry	

Stage	Inclusion or exclusion	Number of articles	Reasons	Number of articles left for analysis
BIM for Safety during construction	Inclusion	753	From Scopus (Round 1 search)	492
	Inclusion	32	From Scopus (Round 2 search)	
	Exclusion	253	Not related to safety during construction in AEC industry	
	Exclusion	40	Cannot download	

2.3 Coding and data analysis

For BIM-based design for safety, research subject, rule source, software tool, and main function were coded; in BIM4Safety during the procurement stage, only one article was recognized as relevant (Sloot et al., 2019); for BIM4Safety during construction, research category, building construction category, site safety management aspects, stakeholder(s), BIM functionality, how BIM is used, other technologies, data analytics methods, case study, real project implementation, safety performance improvement, hazards, and BIM-based health and safety information flow and management were coded for further analysis. Furthermore, detailed BIM functionality and site safety management aspects were assigned unique code as shown in Table 3 and Table 4.

Table 3 Code for BIM functionality

BIM functionality	Sub-functionality	Code
Visualization	Visualization of form	V1
	Construction process simulation	V2
	4D visualization of construction schedules	V3
	Visualizations of process status	V4
Automation	Automated generation of drawings and documents	A1
	Automated generation and evaluation of construction plan alternatives	A2
	Automated conflict/clash detection	A3
	Automated predictive analyses	A4
	Direct Information Transfer to Support Computer-Controlled Fabrication	A5
	Online communication of product and process information	A6
	Provision of context for status data collection on-site/off-site	A7
Database	Store and manage the information	D1
	Providing several exporting mechanisms (such as Industry foundation classes(IFC), relational database, DraWinG (DWG), and so on)	D2

Table 4 Code for site safety management aspect

Site safety management aspect	Detailed site safety management aspect	Code
Health and safety management system	Hazard identification	H1
	Hazard communication	H2
	Hazard prediction	H3
	Hazard assessment	H4
	Safety training/education	H5
	Safety planning	H6
	Job hazard analysis (JHA)/Job safety analysis/task analysis	H7

Site safety management aspect	Detailed site safety management aspect	Code
	Site safety inspection	H8
	Site emergency response	H9
	Site safety monitoring	H10
	Temporary structure	H11
	Heavy equipment management	H12
	Work zone	H13
	Risk paths reasoning	H14
	Risk prevention	H15
	Risk identification	H16
	Risk analysis	H17
	Risk assessment	H18
	Near-miss event identification	H19
Human Factors and safety behaviour	Worker safety behaviour	F1
	Safety awareness/attitude/motivation	F2
	Worker situation awareness	F3
	Worker safety knowledge/competency	F4
	Communication and collaboration	F5

3 Results

3.1 BIM-based safety in design

3.1.1 Definitions and concepts

The concept of safety in design (SiD) is defined as: *"The practice of anticipating and "designing out" potential occupational safety and health hazards and risks associated with new processes, structures, equipment, or tools, and organizing work, such that it takes into consideration the construction, maintenance, decommissioning, and disposal/recycling of waste material, and recognizing the business and social benefits of doing so."* (Schulte et al., 2008) (p115). Globally, the concept of SiD takes various names. For example, it is called Prevention through Design (PtD) in North America, Design for Safety (DfS) in Singapore, Safe Design in Australia, and Construction (Design and Management) (CDM) in the UK (these terms are used interchangeably in this report). These terms share the core principle that designers should either 'design out' or minimize health and safety risks through safe designs. Safety in Design (SiD) is the process of integrating hazard identification and risk management of a project's lifecycle early in the design phase.

Since the introduction of the New Zealand Health and Safety at Work Act 2015 (HSWA), Safety in design has become a statutory requirement for designers to eliminate or minimize health and safety risks for downstream stakeholders. This policy and regulation change is supported by the evidence that SiD has positive impacts on construction site safety (Behm, 2005; Gibb et al., 2004; Hecker et al., 2001; Smallwood, 1996) and that DfS is a viable means for improving construction safety (Gambatese et al., 2005). For example, Gibb et al.(2004) found that 47% of 100 construction accident cases the authors reviewed were associated with the permanent design. Similarly, Behm (2005) found that 42% of fatalities reviewed were linked to the DfS concept. In addition, DfS has demonstrated effectiveness in lowering costs and improving productivity and quality (Howe, 2008).

Recent years have seen increasing applications of BIM to SiD. The increased adoption of BIM for vertical building and horizontal infrastructure projects provides opportunities to identify hazards earlier and support designers to address them. For safety purposes, BIM can be treated as a database and platform for visualization and communication. It is the kernel of information management shared by stakeholders involved in the whole project lifecycle. It has been used for model authoring, visualisation, clash detection, and construction planning and scheduling.

Empirical evidence exists that 3D BIM information is superior to 2D with respect to safety hazard recognition (Hardison & Hallowell, 2018). However, most commercial BIM software and platforms do not support automatic safety modelling and safety risk assessment. Recent research efforts were focused on developing rule-based systems for identifying hazards, assessing safety risks, and recommending control measures.

3.1.2 Automatic rule checking to hazard management

A rule-based checking system can be defined as a piece of software that evaluates a BIM model against pre-developed rules so as to identify issues of interest and return reports (Eastman et al., 2009). From a construction safety perspective, its primary purpose is to flag hazards and recommend control measures by extracting relevant data (e.g., objects and their attributes) from a BIM model and executing computable rules that are developed based on multiple sources (e.g., safety regulations, standards, and best practices). Generic processes of BIM-based rule checking for design for safety are illustrated in Figure 3.

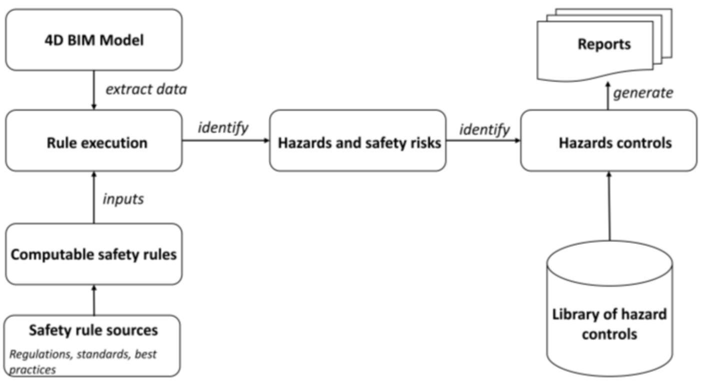

Figure 3 A generic system architecture of BIM-based safety rule checking

Sijie Zhang et al. (2013) is a seminal work that proposes a framework for the BIM-based automated safety-rule checking platform. The rule checking consists of six main steps:

[1] collect and analyse a BIM 3D and 4D (3D plus time) model with work breakdown structure, schedule, and quantities,

[2] develop machine-readable safety rules and a library of control measures based on construction safety standards, best practices, and guidelines,

[3] execute rules against the 4D BIM model,

[4] identify hazards,

[5] identify corrective actions and control measures,

[6] generate reports.

The information extracted from the 4D BIM model is used as the basis for checking geometric features (e.g., length, width, etc.). Thus, a parametric model is essential for the rule-checking process. The information carried in each building object, such as object name, type, attributes, relationships and metadata, including object identification (ID) number, date, and author creating model elements, is mapped and compared to the computable rules. In this study, the results of safety checking were reported in two different forms: (a) visualization of applied safety protective equipment and (b) table-based check of the results showing detailed information from the model and the applied solution. An example of a rule is shown in Figure 2, in which the content in the green box means building objects, orange means object attributes, and red means prevention systems.

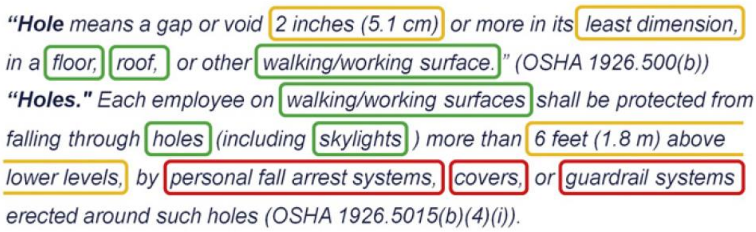

Figure 4 A rule example (adopted from Zhang et al. (2013))

The rule-based checking algorithms developed in this study consist of nine steps, as shown in Figure 5. Sijie Zhang et al. (2013) demonstrated a rule-based algorithm prototype for fall protection based on the BIM software, Tekla Structures.

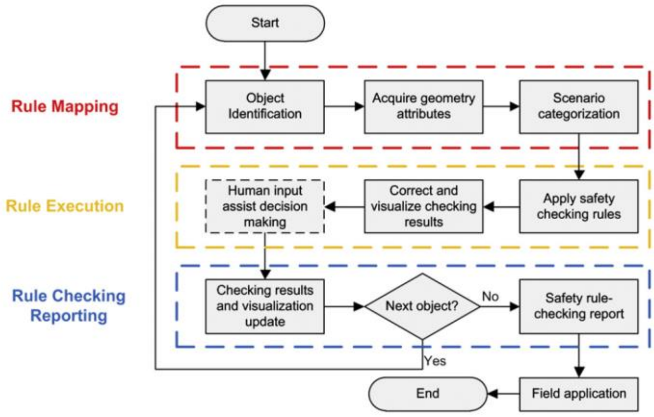

Figure 5 The rule-based checking algorithms (adopted from Zhang et al. (2013))

Melzner, Zhang, et al. (2013) implemented the safety rule-checking platform developed by Sijie Zhang et al. (2013) on a high-rise building project. Rules were developed based on fall protection regulations from both the USA and Germany. The case study suggested that BIM can effectively assist the decision-making process for fall protection equipment in the design and planning stage. Also, Sijie Zhang et al. (2015) applied the rule checking system to multiple case studies, where fall hazards were identified, and prevention planning was tested. The first case study compared manual to automated safety modelling. Results suggested that automated modelling takes a shorter time, requires little safety knowledge, is easy to update, but has a low level of detail. The second case study demonstrated safety checking results dynamically based on the project schedule. Dynamic safety modelling can keep a human decision-maker in the loop of protective safety hazard identification and prevention.

Similarly, Qi et al. (2014) developed a BIM-based PtD (prevention through design) tool using a rule-checking system. Solibri *Model Checker* and *BIM Server* were selected as the software platforms in this paper. They classified model check software into three types based on how friendly they were in regard to their user interfaces used to compile PtD suggestions into computable rules, as presented in Table 5. This study complied the computable rules with the general-purpose property rule template embedded in the Solibri Model Checker. A limitation of the study is that it did not include the construction schedule as a parameter. As such, a dynamic safety analysis was not allowed.

Table 5 Three types of model check software

Type	**Features**	**Example software**
I	The database can be queried by directly using a programming language	Open-source software tool: *BIM Server*
II	Adopts a user-friendly code builder or code editor, which reduces the amount of unfamiliar syntax the engineers have to address	Solibri *Model Checker* *BIM Services*
III	Adopts the natural language interface; Only a small portion of the rules can be successfully transferred in this way	No software of this kind was used as the platform for a PTD tool

More recently, Hossain et al. (2018) developed a BIM-based rule checking system for DfS. The system consists of three main steps:

[1] a Reasoning Engine which reads BIM compliant digital model in IFC format and comprises a set of safety checking algorithms

[2] The reasoning engine compares the physical parameters of the facility in BIM (either readily available in the BIM model or some inferences are done for connectivity, distance, height and so on) against the DfS rules.

[3] The resultant output is the list of identified design risks/hazards which are visualized and tagged in the BIM compliant 3D model and recorded in a Risk Register.

3.1.3 Formalized DfS knowledge base

Most safety rules, regulations, and standards have been written in human languages, which are not easily computable. A formalized knowledge base forms a basis for rule-checking systems. Hossain et al. (2018) present a structured rule-based DfS knowledge library that can be retrieved as a stand-alone knowledge database to be used by the designers for DfS. The knowledge base can be integrated with the BIM platform to enable a BIM-integrated risk review system. The rule was developed based on a six-level taxonomy hierarchical model: design topic, design element, condition/work activity, constraint, safety risk, and DfS required design features, as shown in Figure 6. An example of the rule is shown in Figure 7.

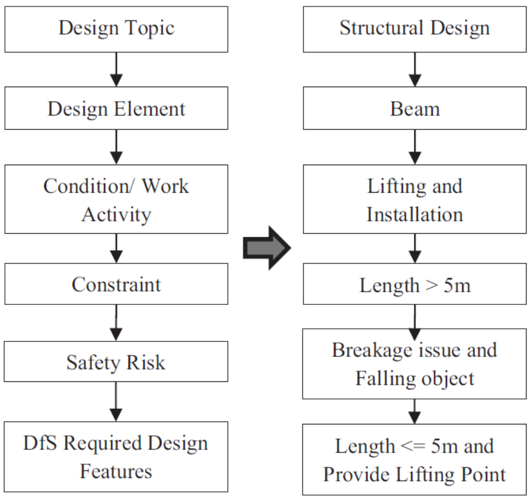

Figure 6 A six-level taxonomy hierarchical model

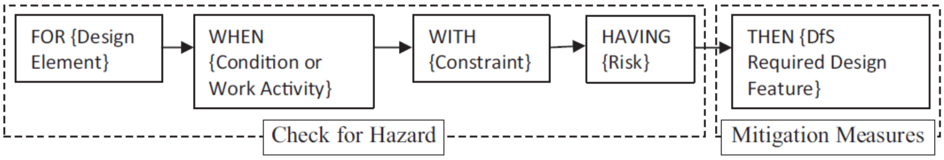

Figure 7 Rule structure

The rationale behind the rule structure is that different design elements may pose different risks under different conditions and constraints. Different "required design" features may need to be applied to mitigate the risk based on the condition and constraint. A major advantage of the rule structure is that it can deal with more complex design scenarios by linking design elements with not only its geometry but also construction activities. To manage the rules efficiently, this study classifies rules into three types: Atomic Rule, Meta Element Rule and Meta Rule (Table 6).

Table 6 Three types of rules

Type	Definition and feature
Atomic Rule	Lowest level rule every constraint associated with a design element makes one atomic rule
Meta Element Rule	A collection of few atomic rules consisting of some conditions, constraints and risks associated with a design element. It applies to a design element with all possible Conditions or Work Activities, Constraints and Risks.
Meta Rule	a high level rule that applies for several design elements with common condition, constraint and risk.

Being consistent with the rule structure, the DfS rule-based knowledge library has six sub-libraries:

[1] design topics or design disciplines,

[2] the list of design elements for each design topic,

[3] a list of conditions or work activities (referred as Meta Condition) associated with different work phases of a building's life cycle.

[4] contains three tables for physical constrain, material constraint and property set constraint, respectively,

[5] the list of risk narratives that may be encountered during the life cycle of building projects,

[6] mitigation narratives that consist of both design suggestions and construction suggestions.

3.1.4 BIM-based risk assessment systems

One of the limitations of rule-checking systems is that safety risks are not quantified in terms of severity and consequence.

Jin et al. (2019) developed a PtD tool for supporting designers to assess construction risks during early phases of multi-storey building projects at an activity level and on a daily basis in a 4D environment.

The risk assessment consists of four main steps:

Step 1: safety risk quantification for design elements

Step 2: incorporating risk values with 4D BIM model

Step 3: 4D model simulation and risk assessment analysis

Step 4: design alternative selection and model acceptance

Although the tool is able to quantify the safety risk at the activity level, it is unable to identify what hazards are involved in the building design and construction activity. The risk score assigned to a certain building element represents an aggregate value of all possible hazards.

Lee et al. (2020) presented a comprehensive BIM-based safety risk assessment tool for PtD. The tool consists of BIM-based hazard identification algorithms and a risk quantification module. The risk of a particular hazard is quantified in terms of likelihood and severity. Residual risk rating was also calculated after the control measure was implemented.

Similarly, Lu et al. (2021) developed a Revit plug-in that assesses safety risks during the design phase. In this study, the safety risk is identified as the product of likelihood, consequence and exposure. The likelihood index is divided into the fatality frequency index and the days-away injury frequency index. The exposure index for occupation *i* (EI*i*) is determined by the quantity (Q*j*) related to the material of construction process *j*, and the unit labour hours involved in construction process j. Building information extracted from Revit is mapped with construction planning data for risk assessment, as shown in Figure 8.

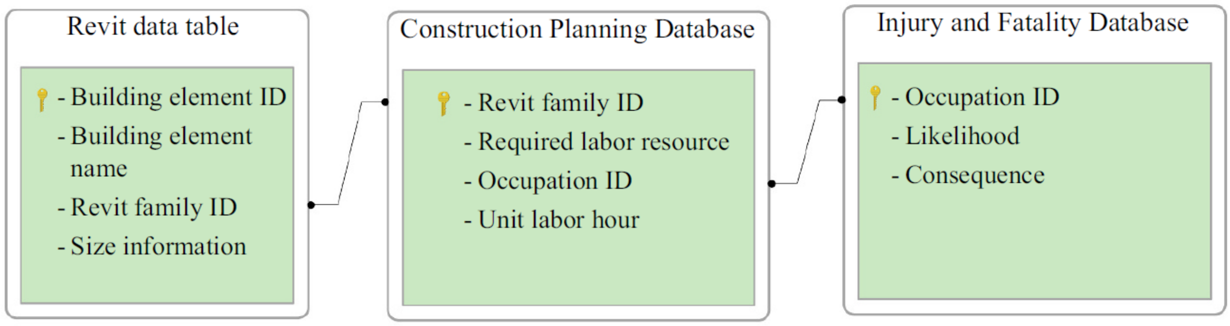

Figure 8 Information mapping process

3.1.5 Data-driven systems

Recent years have also seen applications of data mining and machine learning techniques to BIM-based tools for both DfS and pre-construction safety planning. For example, A. J.-P. Tixier et al. (2017) adopted an attribute-based approach that leverages textual safety-related attributes (e.g., building elements, equipment, tools, working environment, etc.) to identify safety clashes. Safety clashes were defined as "incompatibilities among fundamental attributes of the work environment that contribute to construction injuries". The authors provided an example: *confined workspace* and *small particle (e.g., dust, sand, and* *other airborne particles),* which is considered a clash because the aggregate of the two attributes poses a greater risk than the two attributes in isolation. Data were collected from 5298 injury reports, and Graph mining and hierarchical clustering on principal components (HCPC) were applied to identify candidate safety clashes. The method can be integrated with BIM by extracting attributes from a 4D BIM model and visualizing the safety clashes in BIM.

3.1.6 A summary of current progress and limitations

A brief summary of previous research on BIM-based SiD is presented in Table 7. The results of the review suggest that previous research efforts were focused on developing BIM-based rule checking and risk assessment systems. Several knowledge bases have been developed to support rule-based reasoning and risk assessment processes. In these research efforts, BIM is mainly used as a database, and visualization platform from which objects and their attributes were extracted as inputs for reasoning and assessment, and outputs (e.g., hazards and control measures) are displayed to facilitate communication. Fall hazards were the main research object, as it is closely associated with the attributes of building elements (e.g., opening, roof edge). Machine learning and deep learning techniques are found useful to generate new knowledge from big data. Overall, the research advancements show potential to improve the current SiD process.

Table 7 Previous studies of BIM-based systems for DfS

System	Studies	Country and region	Summary of the study
Rule-checking systems	(S. Zhang et al., 2013)	United States	This paper applies BIM-based safety rule checking algorithms to detect safety hazards and suggest preventive measures.
	(Melzner, Zhang, et al., 2013)	Germany	This paper presents a case study that implements the safety rule-checking platform on a high-rise building project
	(Qi et al., 2014)	China	This paper develops a BIM-based PtD tool using a rule-checking system. Solibri *Model Checker* and *BIM Server* were selected as the software platforms in this paper.
	(S. Zhang, K. Sulankivi, et al., 2015)	United States	BIM-based rule checking to identify hazards and control measures
	(Hongling et al., 2016)	China	BIM-based safety rule checking
	(Hossain et al., 2018)	Singapore	DfS rule-based knowledge library Intelligent BIM integrated risk review system. help designers identify risk related to their design element along with required design features
	(Yuan et al., 2019)	China	BIM-based PtD knowledge base. BIM-based safety rule checking, identifying hazards and controls
BIM-based safety risk assessment system	(Jin et al., 2019)	United States	4D BIM-based risk assessment with a risk calculation method
	(Lee et al., 2020)	Korea	BIM-based PtD to identify hazards and assess risk
	(Lu et al., 2021)	China	BIM-based rule-based safety risk assessment

System	Studies	Country and region	Summary of the study
	(Malekitabar et al., 2016)	Iran	BIM-based risk drivers
BIM-based data-driven system	(A. J. P. Tixier et al., 2017)	France	BIM-based safety clash detection, detect and flag safety clashes
Ontology-based system	(S. Zhang, F. Boukamp, et al., 2015)	United States	BIM and ontology-based automated safety planning for job hazard analysis.

Despite these advancements, the adoption of these developed techniques in practice seems very limited. The review of the case studies indicated that people have begun to perform SiD within the BIM environment, such as using 4D animation to review, assess, and communicate construction hazards and risks. However, these intelligent techniques are yet to be implemented in practice. There are a number of significant research gaps to be filled before they can be implementable. First, there is a strong need to develop a comprehensive knowledge base that enables identifying most of, if not all, hazards, especially those caused by the spatial and temporal relationships among building elements and construction activities. This means future research efforts should be made to investigate how to identify more complex hazardous scenarios based on the information collected from a BIM model. The rule structure proposed by the researchers lays a basis to develop such a comprehensive database. Second, how these techniques work through different design phases (i.e., concept, developed, and detailed design) needs to be investigated. As the Level of Development (LoD) of building elements evolve, how the rule-checking systems and algorithms accommodate the progressive information model throughout the design stage needs further investigation. In addition, future studies need to be conducted to investigate how BIM-based SiD fits in existing SiD methods and processes, such as the Construction Hazard Analysis Implementation Review (CHAIR) introduced by the Australian Council of Building Design Professions and the Royal Australian Institute of Architects.

3.2 BIM-based health and safety in procurement

3.2.1 BIM-based project delivery method

Although BIM is seen as a game-change technology and method, BIM adoption and implementation is still a challenge for the construction industry. Consequently, these barriers to the uptake of BIM are barriers to realising the benefits of BIM for Health and Safety. Several significant legal and contractual risks are involved in a BIM project, as summarized in Table 8.

It is believed that clients or owners play a significant role in promoting the adoption of BIM in construction projects. Government, as a public client, can drive significant improvements in time, cost, quality, and safety through the use of BIM as a kernel of the information management process. The UK Government required full collaborative 3D BIM (with all project and asset information, documentation and data being electronic) as a minimum in public projects by 2016. The policy has led to a significant increase in the adoption of BIM processes. More recently, the UK Government has mandated the use of BIM in all high-rise residential buildings with a height of 18 meters and more.

Table 8 legal and contractual risks of BIM

Legal and contractual risks	Descriptions
Contractual framework for incorporating BIM	• Lack of an appropriate contractual framework that incorporates BIM in project management processes; • Unclear contractual relationship • Unclear risk allocation
Model and information management	• who appoints the model manager? • Who bears the costs? • Issues related to model access, security, transmission, archiving, transmitting, and software interoperability • powers and responsibilities of the model manager
Intellectual property	• The intellectual property of BIM information • joint authorship issues • Confidentiality for the information shared during the BIM process
Reliance on data	• Who is responsible for errors in its contributions? • Risk of inaccurate information

Arshad et al. (2019) identified fourteen significant risks of BIM from ten published taxonomies, five standards and three custom BIM contracts. A survey study was conducted to collect data from BIM experts and industry practitioners regarding the mitigation strategies to the risks. Based on the data, the study proposed and formalized a contractual framework designed for a design-bid-build (DBB) delivery system. Key BIM risks and mitigation strategies are specified in the contractual framework (Table 9).

Table 9 Summary of proposed risk mitigation strategies for DBB projects

BIM risks	**Mitigation strategies**
Intellectual property	Copyrights and any information extracted shall remain with the Architect/Engineer (A/E).
Professional liability	The A/E or any data provider (contractor or third party) is responsible for its duty and shall be liable for its input data.
Conditions of contract	The A/E shall provide a common data environment, and a common file format will be developed in the BIM execution plan.
Data Interoperability	Modelling deliverables and sharing shall be discussed in the BIM execution plan, and the client will direct the A/E about modelling deliverables.
Protocols, processes, and responsibilities	The client will appoint an information manager who shall chair BIM execution plan meetings.
Data security	Project data shall be saved on network servers with monitored access. Each superseded file shall be saved, and its log shall be maintained.
Cost compensation	The client will bear the costs of model development.
Unclear BIM standards	The contractual framework shall be incorporated into the addendum (ConsensusDOC 301 BIM Addendum) of the standard contract document.
Standard of care and professional negligence	All parties are responsible for their own data input duty.
Admissibility of electronic-based	Digital data in general and BIM (archived and digitally signed data with time stamps) in particular will be treated as part of contract documents.

BIM risks	Mitigation strategies
documents	
Model management difficulties	The BIM model shall be maintained by the A/E in accordance with the BIM execution plan.
Legal validation of design	Non-editable version (2D drawings) to be produced according to BIM protocol and execution plan, which will be presented in local administration.
Lack of software compatibility	Common software shall be decided in the BIM execution plan.
Legislation and judicial precedence	If BIM is used, then this addendum (i.e., ConsensusDOC 301 BIM Addendum) shall govern.

Porwal and Hewage (2013) propose a 'BIM partnering' based public procurement framework to ensure 'best value' in construction projects. The paper presents an approach that facilitates BIM adoption through the framework and a collaborative BIM model for the construction process. The authors claimed that the BIM-Partnering procurement framework could sufficiently address legal, procurement, and cultural challenges.

3.2.2 BIM-based safety in procurement

There are guidelines and standards for BIM implementation in construction projects. These guidelines and standards lay a solid basis to enable BIM-based procurement. However, they have little or no specific detail with respect to health and safety management. The literature review revealed that there is very limited research that investigates the BIM-based health and safety during the procurement stage. Sloot et al. (2019) evaluated the usefulness of 4D BIM model for the contractor's tendering team in developing risk mitigation strategies during the procurement phase. Nevertheless, there have been initiatives that facilitate the integration of BIM and safety into procurement and tendering.

UK BIM for Health and Safety (BIM4H&S) Working Group

UK HSE established a BIM for Health and Safety (BIM4H&S) Working Group in early 2014. BIM4H&S Working Group developed a Project Information Requirements (PIR) template to help the client to specify health and safety information requirements in a BIM project. These requirements were set up based on the PAS 1192-6, and classified into three types: functional, role and process, and information cycle requirements (as shown in Table 10, Table 11, and Table 12).

Table 10 Functional requirements

Functional Requirement (FR)	Requirement	When delivered and used
FR-1	A digital H&S Information RACI (Responsibility, Accountability, Consultation, Information) Matrix shall be established aligned to the information provided by the client to ensure the participants who are to use the information have direct access to it.	• Initially delivered during Brief • Used in Preconstruction, Construction, and Post-Construction

Functional Requirement (FR)	Requirement	When delivered and used
FR-2	The findings of the PHASR (Preliminary Hazard Analysis and Safety Review) conducted by the client (including the identified actions, required risk treatment and established risk objectives) shall be structured into a digital format that enables compliance to be routinely monitored.	• Initially delivered during Concept • Used in Preconstruction, Construction
FR-3	The data construct, tagging convention, application protocol and RACI references for the identified (evolving or accepted) elevated risks shall be established for adoption and use by all participants in a unified manner throughout the project lifecycle. The data construct of the structured outputs relating to elevated risks shall be established to allow filtering, use-of, analysis and proactive risk management through various metrics.	• Initially delivered during Concept • Used in Preconstruction, Construction, and Post-Construction
FR-4	A Risk Study Schedule of all required risk studies, workshops and reviews shall be established and maintained for tracking compliance and effectiveness in the identification, treatment and acceptance of risk.	• Initially delivered during Concept • Used in Preconstruction, Construction, and Post-Construction
FR-5	The Terms of Reference for the Constructability Reviews (at design outset and design completion) and for the Commissioning Risk Study shall be available for reference, preparation and compliance by the attendees.	• Initially delivered during Technical Design • Used in Construction
FR-6	Design team participants shall collaboratively develop and make available a Validation and Verification Information Schedule that is to be made available and maintained to support the validation of the built asset and verify functional performance in compliance with the design intent.	• Initially delivered during Developed Design • Used in Preconstruction and Construction,
FR-7	Project participants and service providers shall develop a tabulated list of H&S information shortfalls and gaps relating to their scope to enable informed resolution and effective risk management.	• Initially delivered during Developed Design • Used in Preconstruction and Construction,
FR-8	Project participants and service providers shall develop a tabulated list of the surveys and investigations required to develop, complete or verify the design or construction solution, enabling effective risk management and H&S management of the survey/investigation activities. The surveys required to prepare digital rehearsals shall also be listed.	• Initially delivered during Concept • Used in Preconstruction and Construction,
FR-9	A project-specific Design Plan that includes the approach to DRM (Design Risk Management) shall be established and available to all participants in the design team. A tabulated list of DRO's (Design Risk Objectives) and CRO's (Construction Risk Objectives) for Health & Safety shall be established and available for routine status and compliance monitoring; the tabulated list shall also be embedded in the Design Plan.	• Initially delivered during Concept • Used in Preconstruction and Construction,
FR-10	A project-specific Construction Plan that includes the approach to CRM and sets out the provisions for emergency events shall be established and available to all participants and service providers undertaking construction work (may be an integral part of the CDM required Construction Phase Plan). A tabulated list of CRO's shall be established and	• Initially delivered during Concept • Used in Preconstruction, Construction, and Post-Construction

Functional Requirement (FR)	Requirement	When delivered and used
	available for routine status and compliance monitoring; the tabulated list shall also be embedded in the Construction Plan.	
FR-11	Based on the identified elevated risks and outcome of the Construction Hazard Review, a tabulated list of the 3D visualisations required to assist in planning the control of construction risks and communicating on-site dangers shall be established and maintained.	• Initially delivered during Developed Design • Used in Preconstruction and Construction, and Post-Construction
FR-12	A schedule of as-built records shall be developed and maintained that tracks the progressive validation of the built asset. It shall be sufficiently detailed to allow compliance monitoring, design validation and verification, and preparation of the CDM 2015 Health &Safety File	• Initially delivered during Construction • Used in Construction, and Post-Construction

Table 11 Roles and process requirements

Roles and process requirement (RPR)	Requirement	When delivered and used
RPR-1	A digital construct shall be established that enables learning points for future use to be entered and catalogued for generalisation and open sharing.	• Initially delivered during Brief • Used in Preconstruction, Construction, and Post-Construction
RPR-2	A digital Skills and Training Matrix shall be established and maintained that is specific to the project. The Matrix shall detail any special training requirements and link to verified copies of certificates. The Matrix shall be formatted to allow periodic compliance monitoring using appropriate metrics.	• Initially delivered during Brief • Used in Preconstruction, Construction, and Post-Construction
RPR-3	A tabulated list of all services providers and suppliers (supply chain) shall be maintained. The list shall be sufficiently detailed to provide evidence that digital requirements and H&S (Health & Safety) information has been requested, provided and shared.	• Initially delivered during Developed Design • Used in Preconstruction, Construction, and Post-Construction

Table 12 Information cycle requirements

Information cycle requirement (ICR)	Requirement	When delivered and used
ICR-1	A digital construct shall be established within the CDE (Common Data Environment), that is data input / information outputs, for the H&S information wanted, needed or required by the client that can be routinely updated and accessed for use as intended.	• Initially delivered during Brief • Used in Preconstruction, Construction, and Post-Construction
ICR-2	H&S information provided by the client shall be structured into a digital format for appropriate use by participants and service providers to fulfil their legal duties and contractual BIM obligations throughout the project life cycle.	• Initially delivered during Brief • Used in Preconstruction, Construction, and Post-Construction
ICR-3	The findings of Reviews and Risk Studies (including the identified hazards, proposed risk treatments and agreed	• Initially delivered during Concept

Information cycle requirement (ICR)	Requirement	When delivered and used
	actions) shall be structured into a digital format that enables resolution and compliance to be routinely monitored and available for reference by those affected.	• Used in Preconstruction and Construction
ICR-4	A structured digital information format shall be established that enables the following H&S information to be accessed, filtered and used by other participants in planning, managing and controlling H&S risks: • key design decisions; • design assumptions; • sequences mandated by design; • construction techniques mandated by design; • safety critical factors or features; • elevated risks; • risk treatment that must be verified; • safety provisions designed-in; • elevated/significant safety risks designed-out; • complex lifting operations; • Category II & III temporary works; • key aspects where quality is essential; • design visualisations developed.	• Initially delivered during Concept • Used in Preconstruction and Construction

3.2.3 Tender assessment for BIM related Health and Safety capability

London et al. (2021) conducted a study that aims to enhance the ability of the government to equitably and precisely assess a tenderer's capacity to meet the elevated workplace health and safety (WHS) standards envisioned to be set by a BIM-informed WHS management framework. To date, two reports have been published. The Phase one report suggests that it is essential for clients to demonstrate leadership to establish health and safety requirements (e.g., client information requirements and responsibility matrices) prior to tendering as a priority. The second phase of the research project aims to identify preferred procurement models and best practices to evaluate construction health and safety management in BIM-enabled project proposals and recommend the best way for public clients to evaluate the quality of construction health and safety management during the BIM-enabled tendering documents. They conducted three case studies located in NSW, Australia and 15 semi-structured interviews. The data were analysed to develop a Decision Framework. The framework has two components. The first component focuses on assisting clients in showing leadership and how to create the various information requirements. The second component is more focused and will assist clients in developing strategic project information requirements to inform future project-specific project information requirements. The authors suggested that the first step to increasing the adoption of BIM for construction health and safety is client commitment to creating the enabling environment.

3.3 BIM-based site health and safety management

3.3.1 Research by countries and regions

As shown in Figure 9, the reviewed academic papers are distributed based on the first author's affiliation and country.

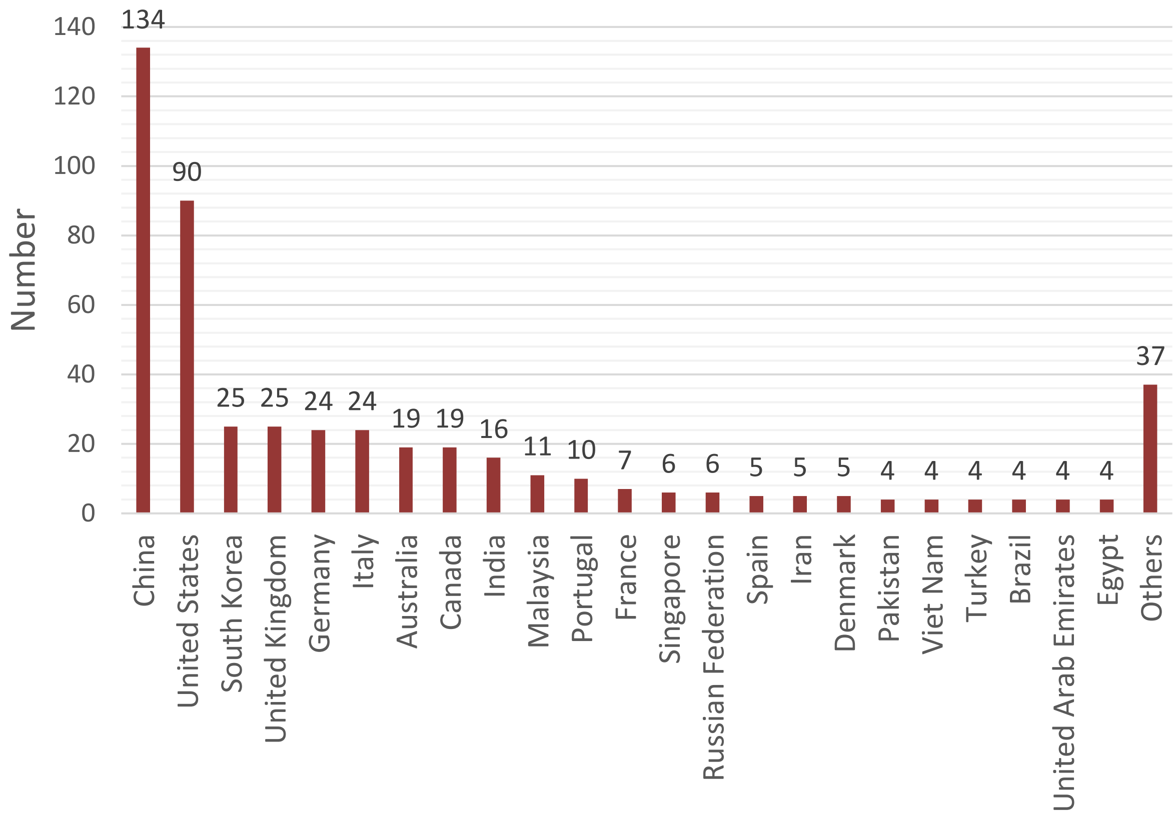

Figure 9 BIM-based construction safety publications by countries and regions

3.3.2 BIM functionality & site safety aspect matrix

This section reports results of how BIM was used for which site safety aspect based on the BIM functionality and site safety aspect matrix analysis.

3.3.2.1 BIM-based safety planning

The purpose of safety planning is to set out how safety risks will be identified, assessed, controlled, and communicated in the construction work that will be undertaken. As a part of construction production planning, safety planning provides a project team with the opportunity to prevent accidents by proactively managing safety risks. A set of preparatory policies, procedures, rules, resources, and relevant personnel are put in place to create a safe environment for workers. A significant output of safety planning is a safety plan that includes, but is not limited to, the following aspects:

- ✓ Immediate actions to take
- ✓ PPE (personal protective equipment)
- ✓ Procedures to secure the area
- ✓ Policy and procedure to notify hazards and incidents
- ✓ Training
- ✓ Emergency planning
- ✓ Incident recording and investigation
- ✓ Hazard register and control

No matter how satisfactory the safety planning is, there will always be gaps between work-as-imagined and work-as-done due to the site dynamics. Traditional paper-based safety planning practices that rely on subjective experts' experience seem ineffective and inefficient in bridging the gaps. Recent years have seen growing research interests in applying BIM to enhancing site safety planning. Some of the systems developed for SiD can also be utilized for pre-construction safety planning. For example, the rule checking system developed by Sijie Zhang et al. (2013) is also helpful for safety planning. The 4D BIM model provides attributes of building objects and the sequence of construction activities, which help people identify and link safety risks with both building elements and tasks. To enhance construction safety planning, Choe and Leite (2017) established a site temporal (potential hazards exposure situation) and spatial (dangerous zone positioning) information integrated 4D safety planning framework. A case study was conducted to test the framework. The results suggested that risky activities, days, and zones can be prioritized when the project schedule contains activity information regarding the number of workers, including occupation types and zoning plans.

Tran et al. (2021) apply the case-based reasoning method to develop a novel hazard identification approach through spatial-temporal exposure analysis (HISTEA) to aid safety planning by information from accident reports. The HISTEA integrate three modules: (1) spatial-temporal hazard investigation (SHI), (2) spatial-temporal condition identification (SCI), (3) safety information integration (SII). Furthermore, an H&S BIM-based design and validation workflow target was created to support virtual inspections and information-based analysis for safety planning (Getuli et al., 2017).

To summarize, three main functionalities of BIM, including visualization, automation, and database, were applied to enhance safety planning, as shown in Table 13.

Table 13 BIM functionalities applied for safety planning

BIM functionality		**Studies**
Visualization	V1 Visualization of form	(Getuli et al., 2017; Golovina et al., 2016; Melzner, Zhang, et al., 2013; S. Zhang et al., 2013)

BIM functionality		Studies
	V2 and V3 4D visualization of construction schedules	(AlSaggaf & Jrade, 2021; Choe & Leite, 2017; Shang & Shen, 2016; Tran et al., 2021)
Automation	A2 Automated generation and evaluation of construction plan alternatives	(Melzner, Zhang, et al., 2013)
	A3 Automated conflict/clash detection	(AlSaggaf & Jrade, 2021; Marzouk & Abubakr, 2016; Shang & Shen, 2016; Tran et al., 2021; S. Zhang, J. Teizer, & N. Pradhananga, 2015; S. Zhang, J. Teizer, N. Pradhananga, et al., 2015)
	A6 Online communication of product and process information	(Choe & Leite, 2017)
Database	D1 and D2 Store and manage the information; Providing several exporting mechanisms (such as Industry foundation classes(IFC), relational database, DraWinG (DWG))	(Bansal, 2011; Chavada et al., 2012; Y. Fang et al., 2016; Getuli et al., 2017; Golovina et al., 2016; Golparvar-Fard et al., 2011; H. Kim et al., 2016; K. Kim et al., 2016; M. Li, H. Yu, & P. Liu, 2018; Melzner, Zhang, et al., 2013; HyounSeok Moon et al., 2014; Park & Kim, 2013; Park et al., 2017; Pham et al., 2020; Schwabe et al., 2019; Wang et al., 2015; Zhang et al., 2016; S. Zhang et al., 2013; S. Zhang, J. Teizer, N. Pradhananga, et al., 2015)

3.3.2.2 BIM-based hazard management

In general, hazard management consists of activities like hazard identification, communication, prediction, assessment, and job hazard analysis.

S. Zhang, F. Boukamp, et al. (2015) developed an ontology to represent, organize, store, and re-use construction safety knowledge. It includes three main domains: construction product, construction process, and construction safety model. SWRL (semantic web rule language) rules were developed based on the ontology and regulations. A case study that links the ontology with the Tekla BIM model was conducted to automate job hazard analysis (JHA). The advantage of this method is that it can not only identify hazards associated with building objects (e.g., roof) but also those involved in construction activities.

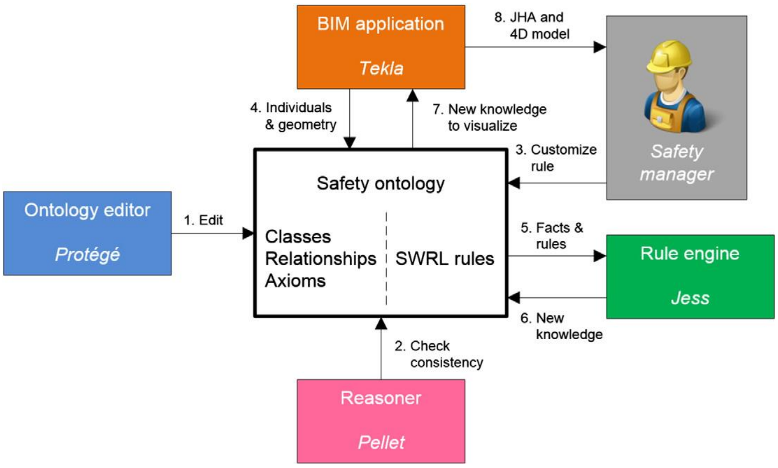

Figure 10 System framework of ontology-based JHA (adopted from S. Zhang, F. Boukamp, et al. (2015))

Similarly, an ontology was developed by (Ding et al., 2016) to standardise safety risk knowledge and facilitate knowledge reasoning and retrieval. A prototype system was developed on Microsoft's .NET Platform to link the ontology with BIM for automated safety risk (hazards) identification. Information was extracted from Revit and Navisworks, and processed together with formalized construction safety risk knowledge. However, this study did not quantify the risks.

Wang et al. (2015) presented a semi-automated method to identify fall and cave-in hazards related to excavation pits and models. Different from previous studies, point clouds were generated using LADAR (LAser Detection And Ranging) sensor to identify temporary geotechnical excavation objects and measure their attributes (e.g., height and slope). In addition, BIM was used as a platform to visualize the fall protection systems.

Meng Li et al. (2018) and M. Li, H. Yu and P. Liu (2018) developed a safety risk identification system (SRIS) and early warning system (SREWS) to manage hazards involved in China's metro construction. SQL database software was used to structure and store construction safety knowledge extracted from multiple sources. The computable knowledge base consists of risk description, premise, risk noumenon, and conclusion. The knowledge base was integrated into BIM-cloud, and BIMQL was applied as an open query language to set up a query system.

(Kim et al., 2015) applied a case-based reasoning approach to retrieving past similar accident cases based on the information extracted from a BIM model (e.g., Object ID and Coordinates of an Object). In this system, a case is defined by a number of features, including work type, building type, work process rate, cost of construction, temperature, age, occupation type, etc.

Note that some hazards or hazardous scenarios are caused by the interactions among construction activities and equipment. To identify those dynamic hazards, (Tran et al., 2021) proposed a novel approach through spatial-temporal exposure analysis, called HISTEA. The approach consists of three modules: (1)

spatial-temporal hazard investigation, (2) spatial-temporal condition identification, and (3) safety information integration. This study advanced the research on BIM-based hazard identification.

Table 14 BIM-based hazard management

BIM functionality		Studies
Visualization	V1 Visualization of form	(Choe & Leite, 2017; Ding et al., 2016; Wang et al., 2015; S. Zhang et al., 2013)
	V3 4D visualization of construction schedules	(Li et al., 2021; Tran et al., 2021)
Automation	A3 Automated conflict/clash detection	(Tran et al., 2021)
	A4 Automated predictive analyses	(K. Kim et al., 2016)
Database	D1 and D2 Store and manage the information; Providing several exporting mechanisms (such as Industry foundation classes(IFC), relational database, DraWinG (DWG))	(Ding et al., 2016; Hossain & Ahmed, 2019; Kim et al., 2015; Li et al., 2021; M. Li, H. Yu, H. Jin, et al., 2018; M. Li, H. Yu, & P. Liu, 2018; Mihić et al., 2018; Park & Kim, 2013; A. J. P. Tixier et al., 2017; Tran et al., 2021; Zhang & Hu, 2011; Zhang et al., 2016; S. Zhang, F. Boukamp, et al., 2015; S. Zhang et al., 2013)

3.3.2.3 BIM-based risk assessment

Adequate site risk knowledge management is indispensable to the success of construction risk assessment. BIM as a visual information-rich and automatic platform can cooperate with ontology and semantic web technology to generate a risk map to semantically inferred interdependences between risks and risk paths. A prototype system based on the methodology was developed by Ding et al.to circuitously enhance the risk assessment process (Ding et al., 2016). Risk Breakdown Structure (RBS), as a systematic method to organize risk factors and events (Holzmann & Spiegler, 2011) was utilized by (Zou et al., 2016) to establish a customized RBS which aims to hierarchically integrate knowledge into BIM to support risk assessment for bridge projects. (Collins et al., 2014) also developed research that strives to merge safety risk factors into BIM for scaffolding construction. For urban deep excavation projects, BIM can serve as a fundamental database to form a BIM-based monitoring system and provide a complete monitoring view. Thus, the complex engineering monitoring information can be visualized and communicated efficiently (Wu et al., 2015). Inspired by behaviour-based safety (BBS), Lee et al. adopted BBS observation checklist and grey clustering model to dynamic analysis construction safety risk. Moreover, a spatial-temporal visual tracking method was developed to promote visual risk assessment (Lee et al., 2019).

BIM, in association with other methods, can perform numerous cutting-edge risk assessments. For instance, a 4D (3D model and schedule) BIM-based temporal-spatial construction safety assessment methodology that aims to detect, visualize, and analyse jobsite collisions was developed by Shang & Shen (Shang & Shen, 2016). Digital twin (DT)-based safety risk coupling model integrated with Internet of

Things (IoT) technology, Apriori algorithm, and complex network can perform live perception and virtual-real interaction for prefabricated building hoisting risk assessment (Z. Liu et al., 2021). In urban underground sites, BIM worked with mobile web service technology to generate a mobile web-based information system (Le & Hsiung, 2014). BIM, combined with geographical information systems (GIS), has the capacity to open the gate to the next level of integration, named 4D GeoBIM (A. H. Liu et al., 2021).

Table 15 BIM-based risk assessment

BIM functionality		Studies
Visualization	V1 Visualization of form	(Collins et al., 2014; Ding et al., 2016; Le & Hsiung, 2014; Wu et al., 2015; Zou et al., 2016)
	V2 Construction process simulation	(Lee et al., 2019)
	V3 4D visualization of construction schedules	(Hosseini & Maghrebi, 2021; A. H. Liu et al., 2021; Shang & Shen, 2016; Zou et al., 2016)
Automation	A1 Automated generation of drawings and documents	(Lee et al., 2019)
	A3 Automated conflict/clash detection	(A. H. Liu et al., 2021; Shang & Shen, 2016)
	A5 Direct Information Transfer to Support Computer-Controlled Fabrication	(Z. Liu et al., 2021)
Database	D1 and D2 Store and manage the information; Providing several exporting mechanisms (such as Industry foundation classes(IFC), relational database, DraWinG (DWG))	(Collins et al., 2014; Ding et al., 2016; Hosseini & Maghrebi, 2021; Kim et al., 2020; Le & Hsiung, 2014; Lee et al., 2019; M. Li, H. Yu, H. Jin, et al., 2018; Lin et al., 2017; A. H. Liu et al., 2021; Z. Liu et al., 2021; Luo & Gong, 2015; Wu et al., 2015; Xu & Wang, 2020; Zhang et al., 2021)

3.3.2.4 BIM-based site safety inspection and monitoring

Site safety inspection and monitoring focus on collecting real-time data to understand the current status of site safety. The main purpose is to identify and control safety risks before they escalate into accidents and injuries. The (near) real-time data is essential to develop situation awareness of both workers and managers. Information related to the leading indicators of near misses and incidents can also be collected and analysed for proactive safety management (Golovina et al., 2019).

(Park et al., 2017) created and evaluated a low-cost automated safety monitoring system for site safety monitoring. The system integrates Bluetooth low-energy (BLE)-based location detection technology, BIM, and a cloud-based communication platform. BLE was used to track workers' location, and unsafe areas were defined in a BIM model. Once unsafe incidents are identified, the warnings will instantly be communicated over the cloud for real-time safety control. Similarly, (Yihai Fang et al., 2016) presented a study that integrates BIM, cloud-based radio-frequency identification (RFID) localization for construction management. The system has the potential to monitor the location of workers, identify hazardous zones, and provide real-time warnings.

(Riaz et al., 2014) reported a study that presents the location data received from wireless sensors using BIM to monitor construction workers in confined spaces. (Arslan et al., 2019a) proposed a 'WoTAS' (Worker Trajectory Analysis System) that use Bluetooth Low Energy (BLE) beacons to monitor the trajectories of workers. The authors applied the Hidden Markov Model (HMM) to categorize workers' movement (e.g., having long steps or many turnings) and visualize the movement in BIM. The authors claimed that WoTAS could help understand workers and machinery movement and contribute to accident reduction. (Ding Liu et al., 2020) developed a system that integrates indoor positioning and inertial measurement unit to capture a worker's conditions (e.g., position, walking speed, and facing direction). The information was then fed into the BIM 3D model to identify if the worker is in a danger zone, close to the roof edge, and in other dangerous situations. The system is able to generate real-time warnings to improve the worker's situation awareness. A digitalized graphical representation method named heat map was developed to perceive and analyse interactive hazardous near-miss situations between heavy equipment and workers; thus, personalized safety performance reports (including blind spot) can be automatically generated for predictive safety planning purposes (Golovina et al., 2016).

(Alizadehsalehi et al., 2020) utilized UAV to monitor the location of potential hazards. The information is then integrated into BIM to facilitate visualization and communication. UAV has advantages in monitoring site safety in large projects, such as highway projects. However, one major drawback is that it is unable to detect indoor environments.

On the health aspect, (Cheung et al., 2018) integrated BIM and a wireless sensor network to visually monitor the hazardous gas level and environmental conditions (e.g., temperature and humidity). The prototype system visualises the conditions on BIM in different colours. It also can alarm and activate the ventilator on-site to remove the hazardous gases.

Table 16 BIM-based site safety inspection and monitoring

BIM functionality		**Studies**
Visualization	V1 Visualization of form	(Arslan et al., 2019a; Arslan et al., 2014; Cheung et al., 2018; Y. Fang et al., 2016; Riaz et al., 2014; Riaz et al., 2017; Wu et al., 2015)
	V3 4D visualization of construction schedules	(Alizadehsalehi et al., 2020; Golparvar-Fard et al., 2011; Tak et al., 2021)
	V4 Visualizations of process status	(Fan et al., 2021; Tian et al., 2021)
Automation	A3 Automated conflict/clash detection	(Tak et al., 2021; Tian et al., 2021)
	A4 Automated predictive analyses	(D. Liu et al., 2020)
	A7 Provision of context for status data collection on site/off site	(Park et al., 2017; Riaz et al., 2014)
Database	D1 and D2 Store and manage the information;	(Alizadehsalehi et al., 2020; Arslan et al., 2014; Cheung et al., 2018; Collins et al., 2014; Costin et

BIM functionality		Studies
	Providing several exporting mechanisms (such as Industry foundation classes(IFC), relational database, DraWinG (DWG))	al., 2015; Dong et al., 2018; Fan et al., 2021; Y. Fang et al., 2016; Golovina et al., 2019; Golparvar-Fard et al., 2011; Guo et al., 2014; Hasan et al., 2021; Liang et al., 2018; Lin et al., 2017; D. Liu et al., 2020; Park & Kim, 2013; Park et al., 2017; Riaz et al., 2014; Riaz et al., 2017; Tak et al., 2021; Tian et al., 2021; Wu et al., 2015; Xu & Wang, 2020)

3.3.2.5 BIM-based safety training and education

BIM play an ancillary role and ordinarily amalgamate with immersive reality technology to support on-site and off-site construction safety training and education. A Proactive Construction Management System (PCMS) merge Unity3D-based data visualisation technology, BIM, and Chirp-Spread-Spectrum-based (CSS) real-time location technology aims to conduct real-time construction elements tracking and post-event visualisation analysis for off-site safety training (Li, Lu, Chan, et al., 2015). Head-mounted displays corroborate with Unreal Engine 4, and BIM can create a realistic VR platform to enhance early hazard recognition, workers' situational awareness, safety behaviour of labours near heavy equipment, and stakeholder's hazard evaluation skill (Hilfert et al., 2016). BIM as a virtual modelling method plus panoramic augmented reality technique can provide a novel safety-related knowledge and conditions visualization methodology and form a virtual data-rich safety training platform. 360-degree panoramas offer an immersive and exhaustive environment for stakeholders to perceive safety challenges to improve the hazard identification training process. Furthermore, 2D images were integrated with BIM assisting trainees in recognizing ten categories of hazards (e.g. gravity, motion, electrical, etc.). (Pereira et al., 2018). Getuli, Capone, & Bruttini developed a BIM and VR-based standardized protocol to benefit safety training standardization, where 4D BIM (3D model and schedule) provides all the information required for the design, management and administration of the VR-based safety training (Getuli, Capone, & Bruttini, 2021).

Table 17 BIM-based Safety training/education

BIM functionality		Studies
Visualization	V1 Visualization of form	(Golparvar-Fard et al., 2011; Hilfert et al., 2016; Pereira et al., 2018)
	V2 Construction process simulation	(Li, Lu, Chan, et al., 2015)
	V3 4D visualization of construction schedules	(Getuli, Capone, & Bruttini, 2021; Golparvar-Fard et al., 2011)
Database	D1 and D2 Store and manage the information; Providing several exporting mechanisms (such as Industry foundation classes(IFC), relational database, DraWinG (DWG))	(Afzal & Shafiq, 2021; Getuli, Capone, & Bruttini, 2021; Getuli, Capone, Bruttini, et al., 2021; Golparvar-Fard et al., 2011; Hilfert et al., 2016; Li, Lu, Chan, et al., 2015; Park & Kim, 2013; Pereira et al., 2018)

3.3.2.6 BIM-based site emergency response

Marzouk and Daour contributed site emergency response by proposing a BIM-based multiple construction methods-enabled worker evacuation process simulation methodologies including a MassMotion simulation platform (Agent-based simulation for human behaviour under evacuation), Ranking and Selection (R&S) statistical procedures, Multi-Criteria Decision Making (MCDM), and Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method. BIM is used to build an adaptable 3D virtual reality environment, which encompasses building geometry, geographic information, spatial relationships, properties and quantities of building elements (Marzouk & Daour, 2018). Moreover, 4D modelling links elements of the 3D model with the activities of the construction schedule for visualization (Marzouk & Daour, 2018). American academics Kim and Lee applied 4D BIM to automatically generate construction daily evacuation paths, where 4D BIM was utilized as a platform to store information, output information, and perform pathfinding algorithms (Kim & Lee, 2019). Iran scholar Hosseini and Maghrebi establish a framework based on cooperation of 4D BIM and Social Force Model (SFM) to perform virtual-based microscopic simulations where 4D BIM provides authentic geometric and semantic knowledge such as human, schedule, machinery, material data, 3D model, task-based ignition potentiality data, and evacuation instructions (Hosseini & Maghrebi, 2021).

Table 18 BIM-based site emergency response

BIM functionality		Studies
Visualization	V1 Visualization of form	(Hosseini & Maghrebi, 2021; Kim & Lee, 2019; Marzouk & Daour, 2018)
	V3 4D visualization of construction schedules	(Hosseini & Maghrebi, 2021; Kim & Lee, 2019; Marzouk & Daour, 2018)
Database	D1 and D2 Store and manage the information; Providing several exporting mechanisms (such as Industry foundation classes(IFC), relational database, DraWinG (DWG))	(Deng et al., 2019; Getuli, Capone, Bruttini, et al., 2021; Hosseini & Maghrebi, 2021; Kim & Lee, 2019; Marzouk & Daour, 2018)

3.3.2.7 BIM-based temporary structure

Temporary structure (e.g., scaffold) is a significant source of danger. To manage the hazards associated with temporary structures, researchers made efforts to utilize BIM to improve the hazard management processes. For example, in 2014, Collins et al. (Collins et al., 2014) conducted research that activity-specific safety risk factors collected through the survey are linked with 4D simulation (BIM and schedule) to enable visualizing the risk level throughout the construction phase to observe and decrease scaffold-related hazards. In 2016, Kim et al. developed BIM-based automated safety checking algorithms and a safety planning platform to identify hazards associated with crews spatial movements on scaffolding. BIM serve as an information hub to store and process the daily work plans of major subcontractors.

Moreover, BIM combines with safety checking algorithms to identify temporary structure-related safety hazards automatically during the construction simulation. (K. Kim et al., 2016). Kim et al. established two decision-making support frameworks in 2018, 4D BIM (3D building elements plus activities in Critical path method (CPM) schedules) were adopted as a data source and an environment to visualize and detect safety hazards related to scaffolding plans (Kim et al., 2018a; Kim et al., 2018b).

Table 19 BIM-based temporary structure

BIM functionality		Studies
Visualization	V1 Visualization of form	(Collins et al., 2014)
	V2 Construction process simulation	(Kim et al., 2018b)
	V3 4D visualization of construction schedules	(Kim et al., 2018a; K. Kim et al., 2016; Kim et al., 2018b)
Automation	A2 Automated generation and evaluation of construction plan alternatives	(Kim et al., 2018a)
	A4 Automated predictive analyses	(K. Kim et al., 2016)
Database	D1 and D2 Store and manage the information; Providing several exporting mechanisms (such as Industry foundation classes(IFC), relational database, DraWinG (DWG))	(Kim et al., 2018a; K. Kim et al., 2016; Kim et al., 2018b)

3.3.2.8 BIM-based heavy equipment management

Marzouk and Abubakr developed a genetic algorithms-based decision support system to determine types and locations of tower cranes in a construction site where BIM function as (1) provide information that genetic algorithm needed, (2) visualize construction site, (3) automatic clash detection (Marzouk & Abubakr, 2016). An augmented reality based integrated crane operation enhancement system was developed provide a rich information environment. The system consists of (1) field information collector, (2) virtual information collector, (3) construction planner, and (4) integrated AR display. In the system, BIM was used to (1) provide a virtual environment as a replication of the actual construction site, (2) contain information of building component during its entire life cycle, and (3) combine with collision detection mechanism to perform collision detection (Chen et al., 2011).

Table 20 BIM-based heavy equipment management

BIM functionality		Studies
Visualization	V1 Visualization of form	(Marzouk & Abubakr, 2016)
Automation	A3 Automated conflict/clash detection	(Chen et al., 2011; Marzouk & Abubakr, 2016)
Database	D1 and D2 Store and manage the information; Providing several exporting mechanisms (such as	(Chen et al., 2011; Marzouk & Abubakr, 2016)

BIM functionality		Studies
	Industry foundation classes(IFC), relational database, DraWinG (DWG))	

3.3.2.9 BIM-based work zone

Construction activities require a dedicated work space to execute the tasks. Work space is considered an important resource and constraint to manage construction schedules (Choi et al., 2014). Overlapping activities are likely to cause accidents and injuries. One of the significant dangers on-site is that a worker working in a certain zone is struck by objects, or a moving worker enters into a danger zone or blind spot, such as the operation area of a tower crane. These hazards are not associated with a single object or person but are caused by complex spatial-temporal conflicts among objects, materials, tasks, and workers. Workspace conflicts not only decrease productivity but also undermine safety performance. Research efforts were made to identify, analyse, and visualize workspace conflicts based on 4D BIM data and other information. Identified conflicts can help project managers to reschedule and optimize construction activities to minimize or eliminate the conflicts. Workspace conflict analysis generally consists of the following steps:

- Workspace generation,
- Workspace allocation,
- Schedule overlapping check,
- Workspace conflict check,
- 4D simulation for visualizing the workspace conflict.

(S. Zhang, J. Teizer, N. Pradhananga, et al., 2015) developed novel algorithms to extract activity-specific workspace parameters from workers' location data. By visualising the workspace on a BIM platform, conflicts can be detected. The method is useful for project stakeholders to identify workspace conflicts and improve site safety proactively.

(HyounSeok Moon et al., 2014) developed a workspace conflict visualization system using 4D BIM model objects. The study presents a methodology that generates workspaces using a bounding box model (as shown in Figure 11) and an algorithm in order to identify schedule and workspace conflict. The authors presented a case study of a bridge project where the development system was evaluated.

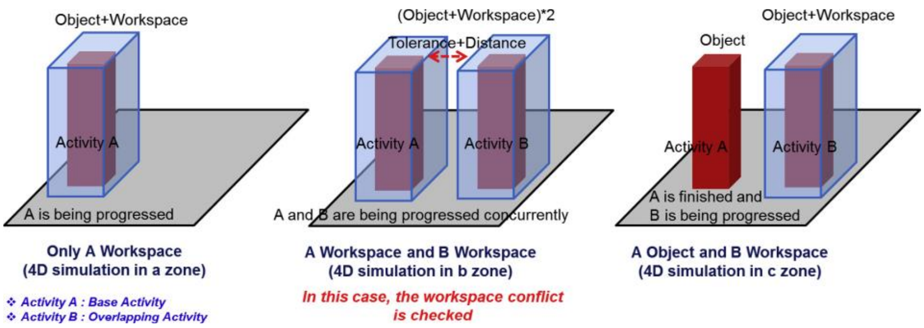

Figure 11 Definition of workspace generation type by bounding box. (adopted from (HyounSeok Moon et al., 2014))

Struck-by heavy construction equipment is a significant cause of fatalities on site. Vulnerable areas on a construction site are often illustrated using *a hazard index heat map*. For example, (Golovina et al., 2016) created hazard index heat maps using GPS data to visualise and monitor close interactions between worker-on-foot and equipment. The method can identify the near-miss events like "worker being in the wrong place at the wrong time".

(Choi et al., 2014) proposed a BIM-based work space planning framework to improve productivity and site safety. The framework consists of five phases, as illustrated in Figure .:

- Develop 4D BIM,
- Identify working and storage-space requirements for activities,
- Represent work space occupation using activity execution plan
- Identify work space conflicts
- Identify pertinent solutions.

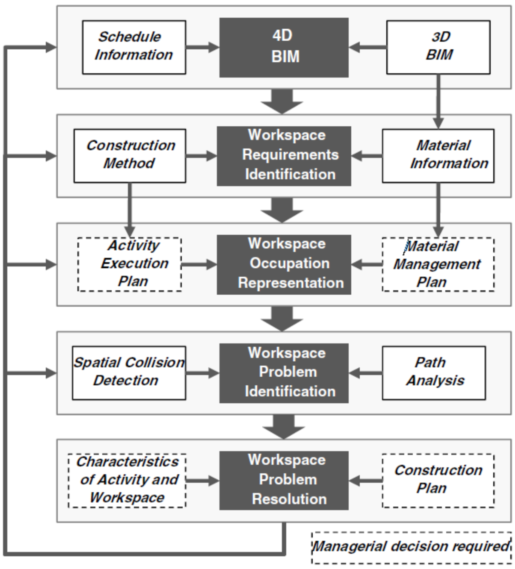

Figure 12 Work space planning process (adopted from (Choi et al., 2014))

Table 21 BIM-based work zone

BIM functionality		Studies
Visualization	V1 Visualization of form	(Arslan et al., 2019b; Choe & Leite, 2017; Golovina et al., 2016; Khan et al., 2021; H. Moon et al., 2014; Yi et al., 2015)
	V2 Construction process simulation	(Lee et al., 2019)
	V3 4D visualization of construction schedules	(Choe & Leite, 2017; K. Kim et al., 2016; HyounSeok Moon et al., 2014; H. Moon et al., 2014; Tak et al., 2021; Tran et al., 2021; S. Zhang, J. Teizer, N. Pradhananga, et al., 2015)
	V4 Visualizations of process status	(Fan et al., 2021)
Automation	A1 Automated generation of drawings and documents	(Lee et al., 2019)
	A2 Automated generation and evaluation of construction plan alternatives	(Melzner, Zhang, et al., 2013)
	A3 Automated conflict/clash detection	(Chavada et al., 2012; Choi et al., 2014; HyounSeok Moon et al., 2014; Tak et al., 2021; Tran et al., 2021; Zhang & Hu, 2011; S. Zhang, J. Teizer, N. Pradhananga, et al., 2015)
	A4 Automated predictive analyses	(K. Kim et al., 2016; D. Liu et al., 2020)
	A6 Online communication of product and process information	(Choe & Leite, 2017; HyounSeok Moon et al., 2014)
Database	D1 and D2 Store and manage the information; Providing several exporting mechanisms (such as Industry foundation classes(IFC), relational database, DraWinG (DWG))	(Arslan et al., 2019b; Astour & Franz, 2014; Bansal, 2011; Chavada et al., 2012; Choe & Leite, 2017; Choi et al., 2014; Fan et al., 2021; Y. Fang et al., 2016; Getuli et al., 2020; Golovina et al., 2016; H. Kim et al., 2016; K. Kim et al., 2016; Lee et al., 2019; D. Liu et al., 2020; Melzner, Zhang, et al., 2013; HyounSeok Moon et al., 2014; H. Moon et al., 2014; Pham et al., 2020; Schwabe et al., 2019; Tak et al., 2021; Tran et al., 2021; Zhang & Hu, 2011; S. Zhang et al., 2013; S. Zhang, J. Teizer, & N. Pradhananga, 2015; S. Zhang, J. Teizer, N. Pradhananga, et al., 2015)

3.3.2.10 BIM-based safety behaviour analysis

Unsafe behaviour is an ongoing safety issue on site. The behaviours that workers perform in their daily jobs can have a direct and immediate effect on health and safety. The classic Domino Theory defines unsafe behaviour, together with unsafe conditions, as root causes of accidents. Researchers utilized BIM to create 3D models and virtual construction simulation systems for safety training (Li, Lu, Chan, et al., 2015). The advanced training program is a part of the proactive behaviour-based safety management system. Combined with real-time location sensors, BIM can be used to identify unsafe behaviour related to personal protective equipment use (Dong et al., 2018) and workers' locations, such as closed to opening, roof edge, and other hazardous areas (Guo et al., 2014).

Table 22 BIM-based safety behaviour analysis

BIM functionality		Studies
Visualization	V1 Visualization of form	(Dong et al., 2018; Li, Lu, Hsu, et al., 2015)
	V2 Construction process simulation	(Dong et al., 2018; Li, Lu, Hsu, et al., 2015)
Database	D1 and D2 Store and manage the information; Providing several exporting mechanisms (such as Industry foundation classes(IFC), relational database, DraWinG (DWG))	(Dong et al., 2018; Guo et al., 2014)

3.3.3 Research by hazards

Previous research within the research area of BIM for construction health and safety has addressed a wide range of construction safety hazards, including fall from height, slip, trip, collision, caught-in-between, struck-by-objects, falling objects, electrical, fire, gas, confined space, high temperature, cave-ins, and those related to hosting and scaffold. As shown in Table 23, because fall from height can be identified by reasoning the inputs extracted from a BIM model, it has been an active research topic. By utilising 4D BIM models, research efforts were also made to address the dynamics on-site, such as the conflicts of workspace.

Table 23 Hazards and related BIM-based research

Hazard	Studies
Fall from height	(Deng et al., 2019; Hossain & Ahmed, 2019; Khan et al., 2019; H. Kim et al., 2016; Kim et al., 2020; Li, Lu, Chan, et al., 2015; Lin et al., 2017; D. Liu et al., 2020; Melzner, Zhang, et al., 2013; Pham et al., 2020; Wang et al., 2015; S. Zhang, K. Sulankivi, et al., 2015; S. Zhang et al., 2013)
Collision	(AlSaggaf & Jrade, 2021; Chen et al., 2011; Golovina et al., 2016; Kim et al., 2020; Lin et al., 2017; Marzouk & Abubakr, 2016; Shang & Shen, 2016)
Slip, trip, and fall	(Lin et al., 2017) (H. Kim et al., 2016; Lin et al., 2017; D. Liu et al., 2020)
Falling objects	(Deng et al., 2019; Dong et al., 2018; H. Kim et al., 2016; Kim et al., 2020; D. Liu et al., 2020; S. Zhang, J. Teizer, N. Pradhananga, et al., 2015)
Workspace conflicts	(Chavada et al., 2012; Choi et al., 2014; Getuli et al., 2020; A. H. Liu et al., 2021; HyounSeok Moon et al., 2014; H. Moon et al., 2014; Schwabe et al., 2019; Tak et al., 2021; Zhang & Hu, 2011; S. Zhang, J. Teizer, & N. Pradhananga, 2015)
Caught-in-between	(Pham et al., 2020)
Struck-by-objects	(Kim et al., 2020; Li, Lu, Chan, et al., 2015; Pham et al., 2020)
Electrical	(Dong et al., 2018; H. Kim et al., 2016; Pham et al., 2020)
Fire	(Hosseini & Maghrebi, 2021)
Gas	(Cheung et al., 2018)
Confined space	(Riaz et al., 2014)
Temperature extreme	(Arslan et al., 2014; Riaz et al., 2014)
Humidity extreme	(Arslan et al., 2014)

Hazard	Studies
Cave-ins	(Fan et al., 2021; Khan et al., 2019; Kim et al., 2020; Lin et al., 2017; Wang et al., 2015)
Natural disasters	(Costin et al., 2015; Getuli, Capone, Bruttini, et al., 2021; Kim & Lee, 2019; Marzouk & Daour, 2018)
Hoisting-related	(Z. Liu et al., 2021; Tian et al., 2021)
Scaffold-related	(Kim et al., 2018a; K. Kim et al., 2016; Kim et al., 2018b)

3.3.4 BIM-related technologies for H&S

Hazard identification is a challenging task. The data extracted from BIM are not adequate to identify all possible hazards. In particular, identifying those hazards that are related to the spatial-temporal relationships among building elements, materials, equipment, tasks, and workers requires multiple information sources. In addition, one of the drawbacks of BIM models is that it needs to be updated based on real construction progress, which is challenging in practice (Sijie Zhang et al., 2013). Other information technologies can bridge the information gaps, such as IoT sensors and 3D laser scanning.

Table 24 Other technologies integrated with BIM

Technologies integrated with BIM	Main functions of the combination	Studies
Internet of things (IoT) sensors	• Tracking equipment, materials, and workers, • Visualize the location on BIM • Compute and analyse distance, proximity, and height of the object and person of interest	(Arslan et al., 2014; Y. Fang et al., 2016; Le & Hsiung, 2014) (Arslan et al., 2019a, 2019b; Arslan et al., 2014; Cheung et al., 2018; Costin et al., 2015; Dong et al., 2018; Fan et al., 2021; Y. Fang et al., 2016; Golovina et al., 2016; Golparvar-Fard et al., 2011; Guo et al., 2014; Hasan et al., 2021; H. Kim et al., 2016; Li, Lu, Chan, et al., 2015; Li, Lu, Hsu, et al., 2015; D. Liu et al., 2020; Z. Liu et al., 2021; Park & Kim, 2013; Park et al., 2017; Riaz et al., 2014; Riaz et al., 2017; Tang et al., 2019; Tomasi et al., 2015; Wang et al., 2015; S. Zhang, J. Teizer, & N. Pradhananga, 2015)
Immersive reality (includes Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR))	• AR can visualize building design and construction process, and thus facilitate safety risk communication • VR is effective to support safety education and training • BIM-based VR can facilitate safety planning	(Afzal & Shafiq, 2021; Chen et al., 2011; Getuli, Capone, & Bruttini, 2021; Getuli et al., 2020; Getuli, Capone, Bruttini, et al., 2021; Hasan et al., 2021; Hilfert et al., 2016; Li, Lu, Hsu, et al., 2015; Park & Kim, 2013; Pereira et al., 2018; Wang et al., 2018)
3D laser scanning	• Model real site conditions and complement the BIM data	(Liang et al., 2018)
Cloud computing	• allows to easily access their 3D models and other services from virtually anywhere	(Costin et al., 2015; Y. Fang et al., 2016; Le & Hsiung, 2014; Z. Liu et al., 2021; Pham et al., 2020)
Computer vision	• Recognize building elements and construction progress • Facilitate 3D model re-	(Golparvar-Fard et al., 2011; Xu & Wang, 2020)

Technologies integrated with BIM	Main functions of the combination	Studies
	construction	
Ontology	• Ontology was used to represent and organize construction safety knowledge bases • Ontology facilitates reasoning	(Arslan et al., 2019a; Ding et al., 2016; Li et al., 2020; A. J. P. Tixier et al., 2017; S. Zhang, F. Boukamp, et al., 2015; S. Zhang, J. Teizer, N. Pradhananga, et al., 2015)
Cyber-Physical System Digital Twin (includes Smart Building and Digital or Smart City)	• Develop a digital model of reality	(Bansal, 2011; Golparvar-Fard et al., 2011; Hasan et al., 2021; Z. Liu et al., 2021)
Game engine	• Used together with VR and BIM, game engine can create and simulate (serious) games for safety education and training	(Chavada et al., 2012; Getuli, Capone, & Bruttini, 2021; Getuli et al., 2020; Getuli, Capone, Bruttini, et al., 2021; Park & Kim, 2013)
Geographic information system (GIS)	• Track the location of objects and workers • Link the location data with BIM	(AlSaggaf & Jrade, 2021; Bansal, 2011; Khan et al., 2021; A. H. Liu et al., 2021; Shirowzhan et al., 2017)
Mobile technologies	• Real-time BIM-based safety information communication	(Arslan et al., 2019b; Park & Kim, 2013; Park et al., 2017; Riaz et al., 2014; Shirowzhan et al., 2017)
Unmanned aerial vehicle (UAV)	• Capture real-time site conditions in images and videos • Facilitate 3D re-construction	(Alizadehsalehi et al., 2020; Tian et al., 2021)

3.3.5 A summary of research achievements and limitations

In academia, significant research achievements advance BIM-based construction health and safety management. Those achievements in hazard management, risk assessment, site safety inspection and monitoring, temporary structure, heavy equipment, and safety training and education are summarised as follows.

Hazard management is at the core of site safety management. Several significant achievements were obtained that advanced BIM-based hazard management practices. Rule-based checking systems were developed to identify hazards and recommend control measures. In these systems, BIM is used as a database and visualization platform. The data extracted from BIM (e.g., object ID and attributes) are mapped with the computable safety knowledge base to enabler rule-based reasoning. Ontology, SWRL, semantic web technologies, SQL, and Backus-Naur form, and other languages were used to convert safety knowledge in natural language to computable rules. These systems have been proven useful to support hazard identification in design, pre-construction, and construction phases.

Despite these advancements, there are several limitations. First, the rule-based checking systems heavily rely on BIM data. Hazards that are closely associated with building elements (e.g., roof edge and opening) are easier to be identified than others (e.g., struck-by, proximity issues, and cave-ins) caused by interactions among construction activities, equipment, and workers. This can explain why previous research efforts were mainly focused on fall from height. When the terrain, site logistics, construction equipment operation, and workers are not included and represented in BIM, it is not possible to identify hazards linked to these objects and people. The Construction Safety Ontology seems to be useful to enhance the coverage, as hazards can be inferred based on not only building elements but also construction activities (4D BIM). However, ontology-based reasoning is data-intensive and thus suffer from the same limitation of the deep reliance on BIM data. In addition, the reasoning performance (e.g., precision and recall rate) is yet to be tested in real projects.

Second, the existing BIM-based rule-checking systems seem suitable for safety in design and pre-construction safety planning, as BIM models are usually developed from a design perspective. Due to the fact that there are always discrepancies between work-as-planned and work-as-done, rule-checking systems that are based on BIM are inefficient to capture reality in real-time. The performance of BIM-based rule-checking systems depends on how accurate the BIM model is to reflect current construction site conditions and schedules. Issues like infrequent model updating, lack of safety equipment modelling, lack of accurate level of details pose major roadblocks for week-ahead safety planning.

To capture the current site conditions, researchers have begun to apply other technologies to complement BIM data. Real-time location sensors, UAV, and laser scanning are proven useful to capture the site dynamics for safety inspection and monitoring. Integration of these technologies enables the development of a digital twin of site safety and thus offers opportunities to improve traditional manual and paper-based site inspection and monitoring. The main advantage (and justification for) of integrating those technologies with BIM is that they can capture the real-time status of project objects and persons that BIM cannot, such as workers' trajectory, hazardous gas level, noise, temperature and oxygen level, and so on. The combined information is essential to improve the level of situation awareness of both workers and managers and therefore support informed decision-making at the worker and project level. The main assumption behind the multi-technology integration is that improved communication and situation awareness results in less unsafe behaviours and safer site conditions. However, this assumption has not yet been tested in real projects.

Another notable achievement is that several artificial intelligence and big data techniques were proved useful to generate new knowledge from a large amount of data (such as accident reports). For example, information retrieval systems that apply case-based reasoning were developed to support learning by retrieving similar past accidents. When linked with the BIM design process, the systems would be useful for designers to perceive the risk level and facilitate design optimization. The majority of previous BIM for safety research is data-based and knowledge-driven, that is, utilizing logic as a tool for representing safety knowledge held by people. Some significant initiatives were made to explore the value of data-driven safety analysis. For example, A. J.-P. Tixier et al. (2017) adopted an attribute-based approach that leverages big textual safety-related attributes (e.g., building elements, equipment, tools, working environment, etc.)) to identify safety clashes. The research adopts a different philosophical perspective, claiming that the new safety knowledge is made of observed data. One of the significant limitations of data-driven approaches is that they rely on a large amount of data for training and modelling, which is often expensive in the construction industry. However, natural language processing (NLP) looks helpful to reduce costs.

It seems that "safety risk" and "hazard" were used interchangeably in previous research. BIM-based safety risk assessment consists of three main components: (1) risk identification, (2) risk quantification, and (3) risk controls. As such, BIM-based risk assessment shares a considerable overlap (i.e., risk identification and controls) with BIM-based hazard management. Researchers have applied risk quantification models (e.g., likelihood and severity matrix) to quantify the level of risk and visualize them in BIM using various colours.

Hazards related to temporary structures (e.g., scaffolding and formwork) have attracted significant research attention in recent years. Researchers are now able to integrate temporary structures into BIM-based automated safety checking systems. Considering that temporary structures are often constructed by subcontractors, safety planning and analysis of temporary structures requires data sharing and coordination. For example, the work by (K. Kim et al., 2016) emphasized the importance of subcontractors' involvement and coordination in safety planning. Scaffold-related safety issues, like falling objects from scaffolds, spatial conflicts with other workspaces, activities in limited access zones, and structural failure, can be identified based on detailed work plans and workspaces. To support scaffold planning, (K. Kim et al., 2016) successfully developed a BIM-based decision support system that can automatically generate multiple scaffolding plans and quantitatively evaluate them regarding safety, cost, and duration. In addition, research has demonstrated that 4D BIM is useful for tower crane selection, allocation, and operation. 4D BIM offers unique advantages over 2D paper drawings in identifying and visualizing possible clashes.

Research has demonstrated that BIM, integrated with VR and game engine technologies, is useful for safety training and education. By providing an immersive virtual environment, BIM-VR based safety training programmes are more effective than traditional in-class lecturer-dominated safety training.

3.4 Guidelines and Standards

Construction is a highly fragmented industry, with multiple stakeholders and most small to medium-sized companies. BIM standards define design methods and processes, information management, collaboration requirements, documentation, roles and responsibilities, and a range of other important aspects. Two sets of BIM standards were reviewed in this study: PAS 1192 framework and ISO 19650 series.

3.4.1 PAS 1192 framework

PAS (Publicly Available Specification) is a standardization document developed in response to an identified market need based on the existing code of practice. PAS documents are usually reviewed within two years to assess where there is a need to revise, withdraw, or become a formal British or international standard. The PAS 1192 framework specified the requirements for the BIM information management regarding the level of model detail, model information, definition, information exchanges, and roles and responsibilities. It consists of a series of PAS documents aiming to achieve BIM Level 2. A brief description of the PAS 1192 documents is presented in Table 25.

Table 25 A brief description of the PAS 1192 documents

Document title	Brief description	Status
PAS 1192-2 Specification for information management for the capital/delivery phase of construction projects using building information modelling	It deals with the construction (CAPEX) phase, and specifies the requirements for Level 2 maturity; sets out the framework, roles and responsibilities for collaborative BIM working; builds on the existing standard of BS 1192, and expands the scope of the Common Data Environment (CDE).	withdrawn *and Replaced by BS EN ISO 19650-1 & BS EN ISO 19650-2*
PAS 1192-3 Specification for information management for the operational phase of assets using building information modelling	It details the requirements to achieve BIM Level 2, focusing on data transfer processes required for the creation of an asset information model (AIM) and to facilitate information exchange with the project information model (PIM).	Withdrawn
BS 1192-4 Collaborative production of information - Fulfilling employer's information exchange requirements using COBie. Code of practice	It defines a methodology for the transfer between parties of structured information relating to Facilities, including buildings and infrastructure.	Current, under review
PAS 1192-5 Specification for security-minded building information modelling, digital built environments and smart asset management	It specifies requirements for the implementation of cyber-security-minded Building Information Modelling (BIM) throughout the construction process.	Withdrawn
PAS 1192-6 Specification for collaborative sharing and use of structured Health and Safety information using BIM	It aims to remedy that by providing guidance on applying H&S information through BIM processes and applications.	Current

PAS 1192-6 is a new document that was added to the PAS 1192 framework. The documents was developed by the BIM4Health and Safety Working Group, with the fund by British Standards Institute (BSI), the Health and Safety Executive (HSE), the Association for Project Safety (APS) and Costain. It provides guidance on applying health and safety information through BIM project phases. It specifies how health and safety information should be produced, shared, used, and managed across the project lifecycle. It supports the progressive development of structured health and safety information for all construction projects.

Specifically, it develops a framework of the risk information cycle, which requires each participant to implement four components (i.e., identify, use, generalize, and share) that provide the foundation and structure for the collaborative use of health and safety information. In addition, it specifies implementation strategies for stakeholders, like clients, designers, contractors, the commissioning team, end-users, and the supply chain.

The standard requires the health and safety information to include the context defining the scope of the work and the elevated health and safety risks. Regarding health and safety information format, it requires to use document table or spreadsheet, COBie, or BIM authoring and project planning applications. To facilitate communication and avoid confusion, it requires that the health and safety information be consistent and all entries follow the same structure. Data reusability is highlighted. Reusable data can be further processed by embedded queries, rules, or by competent persons. In the standard, the risk is modelled and quantified based on likelihood and consequence. The Standard provides a classification of risks, which should be applied in future academic research and practices to research a standardization. An example of a risk table is provided in the standard.

Risk Name	Hazard Category	Risk Description	Assocated Product	Assocated Activity	Assocated Location	Agreed Mitigation	Risk Likelihood	Risk Consequence	Level Of Risk	Risk Documentation	Date Raised
AAM05	Falls	Falling from height / Damage to building	roof light	cleaning and maintenance	atrium	A detail cleaning and maintenance strategy for the building is being developed with specialist consultant. The atrium roof will be designed to be walked on and appropriate access, drainage and slip resistance will be considered.	High	Very High	Very High		2013/05/14
AAM03	Falls	Falling from height; Items falling from height	internal and external façade glazing	replacement	cut back areas of the building	A detail cleaning and maintenance strategy for the building is being developed with specialist consultant.	Low	High	Moderate		2013/05/14
AAM06	Falls	Falling from height / Damage to building	glazing, feature lighting	cleaning and maintenance	roof, bridges,	A detail cleaning and maintenance strategy for the building is being developed with specialist consultant. A travelling beam and demountable cleaning cradle are being considered to allow safe access to all areas.	High	Moderate	Moderate		2013/05/14
AAM07	Falls	Falling from height / Damage to building	glazed screens	cleaning and maintenance	scenic lifts	A detail cleaning and maintenance strategy for the building is being developed with specialist consultant. The cleaning strategy for these screens in close proximity of the lifts will need to be developed further and co-ordinated with the lift subcontractor in due course.	High	Very Low	Moderate	AAM_DRA_07.pdf	2015/08/15
AAM08	Falls	Falling from height / Damage to building	equipment such as Photovoltaic cells, Satellite dishes	cleaning and maintenance	roof	A detail cleaning and maintenance strategy for the building is being developed with specialist consultant.	Moderate	High	Moderate		2013/06/24

Figure 13 An example of risk table

3.4.2 ISO 19650 series

Due to the coming BIM-globalisation, the UK government decided to move from PAS 1192 framework to the ISO 19650 series. The ISO 19650 series is the international standard for managing project information over the life cycle of a built asset using BIM. The principles and requirements set up in the ISO 19650 are consistent with the current PAS 1192 framework. However, there are some differences in terminology.

Table 26 ISO 19650 series

Standard code	Standard title
BS EN ISO 19650-1:	Organization and digitization of information about buildings and civil engineering works, including building information modelling -- Information management using building information modelling: Concepts and principles.
BS EN ISO 19650-2:	Organization and digitization of information about buildings and civil engineering works, including building information modelling -- Information management using building information modelling: Delivery phase of the assets.
BS EN ISO 19650-3	Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM). Information management using building information modelling. Operational phase of the assets.
ISO/DIS 19650-4	Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling — Part 4: Information exchange
BS EN ISO 19650-5	Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM). Information management using building information modelling. Security-minded approach to information management.

Note that ISO 19650-6 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling — Part 6: Health and Safety is currently under development. Once completed, it would be another important international standard for BIM-based health and safety management.

3.4.3 BIM Site Safety Submission Guidelines and Standards by NYC Buildings

New York City (NYC) Department of Building (DOB) initiated a 3D Site Safety Plans Program. The program uses BIM to create and submit electronic site safety plans to the construction industry. The submission is reviewed using BIM, thus improving the compliance review process. In specific, the program offers three main benefits: increased site safety, faster approvals, better service and fewer office visits.

BIM Site Safety Submission Guidelines and Standards were developed and issued to support the practices (NYC Buildings Department, 2013). Autodesk products were chosen by the NYC DOB as BIM software and platform. All submitted files must be compatible with the version of the Autodesk Revit software currently being used by DOB. Submission content should be created using Revit and AutoCAD Architecture and reviewed in Navisworks Manage. For safety analysis and review, the guidelines and standards define the parameters associated with each element. The data to these parameters can be applied to either the pre-defined parameter list of Revit or shared parameters. Details of submission requirements and the review process are also provided. An example of a review comment is shown in Figure 14.

Table 27 Element and parameters

Element	parameters
Construction Vehicle	Type; Manufacturer; Permit Number; Link to Specifications
Cranes	Type; Manufacturer; Permit Number; Link to Permit; Link to Specifications; Link to Building Tie-In Details; Radius of swing and length of boom; Load Capacity
Hoists	Type; Manufacturer; Permit Number; Link to Specifications; Link to Building Tie-In Details
Netting and Guardrails	Height; Link to Detail and Design Drawings; Assembly Materials
Cocoon Systems	Permit Number; Copy of approved CCD1; Link to Detail and Design Drawings; Assembly Materials
Construction Fence and Perimeter Protection/ Enclosure	Height; Material; Permit Number

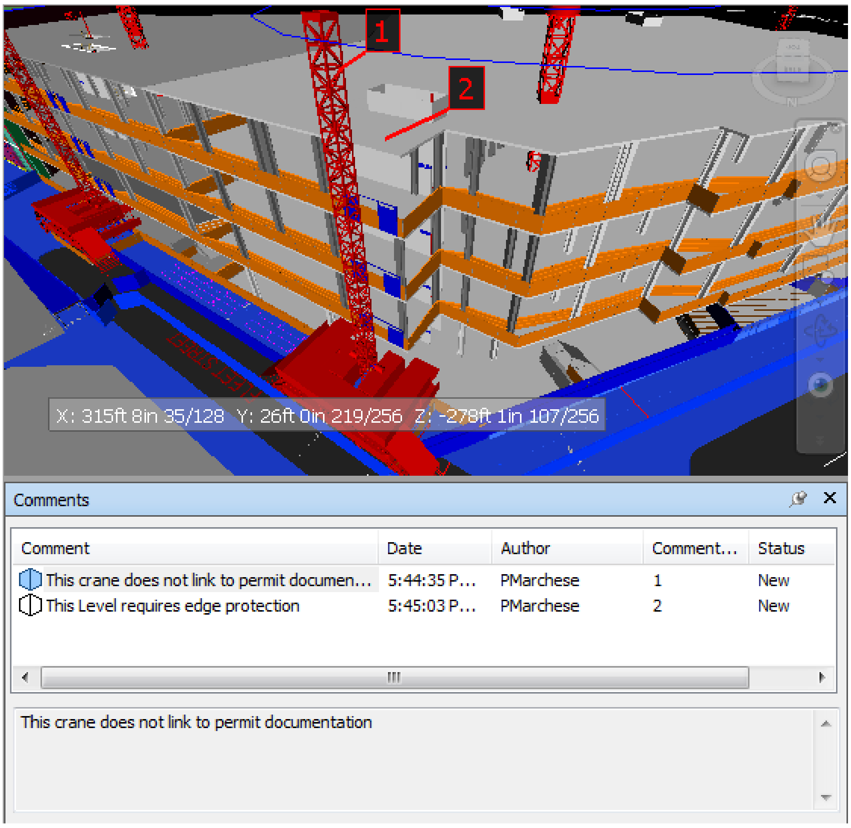

Figure 14 An example of a review comment

3.5 Industry practices and case studies

VTT Technical Research Centre of Finland made pioneering efforts to apply BIM to construction health and safety (Kiviniemi et al., 2011). VTT conducted a BIM Safety project that aims to develop procedures and use of BIM technology for safety planning, management, and communications, as part of the 4D-construction planning. The project was a part of The Safety and security programme of Tekes – the Finnish Funding Agency for Technology and Innovation. The highlight of the project is that seven different field trials were carried out to develop and test the possibilities of BIM technologies for site safety. A brief summary of the details and key results of the field trials is presented in Table 28.

Table 28 Details and key results of seven field trials

Field trial	Details and Key results
Site layout plans and crane reach visualization related to a crane collapse	• An industrial building in Eurajoki, Finland, • Site layout planning experiments carried out using BIM software packages ArchiCAD and Tekla Structures, • The needed temporary construction equipment could be included and presented.
Visualization of wall demolition procedures	• Demolition parts were modelled using BIM-based modelling software Tekla Structures 15, and special tools (Task Manager and Project status visualization) of the software for setting up the 4D visualizations, • Two alternative sequences of demolition work were evaluated and visualised.
Modelling of safety railings	• 3D guardrail components were modelled to be used in BIM-based site safety planning, • Tekla Custom components were used for BIM-based safety modelling. • Tekla Structures lack tools to easily manage temporary structures (such as safety railings)
4D-visualization of floor form work with needed falling prevention solution	• Safety nets were modelled and visualised, • A 3D mold plan can be combined with a Tekla structural model, • 4D scheduling and visualization can be carried out to the mold parts together with cast-in-place concrete parts of the structural model.
Expert analyses with the aid of virtualised construction site	• Visual evaluation of the falling prevention plan was conducted with Tekla Structures model presented on two screens in the CAVE environment, • Only daily basis simulation is possible using Tekla Structures, • More detailed sequence analysis at a construction object-level would be useful for evaluating risks.
Automatic safety analysis using BIM technologies	• Solibri Model Checker software (SMC) has a set of predefined and hard-coded rules that can be modified for safety analysis purposes
Site safety communication and BIM	• Weekly timetable and accident reports were displayed and communicated, • Information display was a good source of knowledge on site affairs.

(Enshassi et al., 2016) conducted a study that surveyed the industry applications of BIM for construction health and safety in the Gaza strip. The results showed that BIM-based hazard identification and recognition was the main use by the industry, which was followed by BIM-based safety training, site layout planning, and falling prevention planning. A number of case studies of UK and US is presented in Table 29.

Table 29 case studies from UK and US

UK	Bond Street to Baker Street tunnel relining project	• Identify hazards and risks through constructability review during the design phase, • A 15% saving in planning, risk assessment, safety and assurance costs was realised. Primarily due to increased efficiency and a reduction in the hours spent in the tunnel, reducing the exposure (and therefore risk) to the workforce. https://www.youtube.com/watch?v=eN2MBIfhxBI
	The Thames Estuary 2100 project (TE2100)	• This project is pioneering the use of a **Common Data Environment** to capture information about flood defence assets, to store health and safety information using a common COBie format, to ensure that this information is kept available and retrievable over the long term. https://www.gov.uk/government/publications/thames-estuary-2100-te2100
	National Grid, Eakring Training Centre	• Using BIM and data rich models as a tool to support design review and process safety reviews, • BIM model facilitates collaborative working, and speeds up the rate of decision-making.
	GlaxoSmithKline	• Bryden Wood’s Design for Manufacture and Assembly (DfMA) solution was adopted to enable rapid deployment of pharmaceutical facilities, • The use of colour-coded components, coordinated through the BIM model, reduced the skills required by workers to complete the step by step assembly process. • Less people, fewer site materials and operations and more formalised process with improved instructions produced a simplified site environment, leading to significant site safety improvements.
US	Southland Industries	• Southland’s Southwest Division launched a new program that utilizes Building Information Modeling (BIM) to eliminate risks before it occurs on the construction site. • With Navisworks, a BIM program, Southland virtually walks a project and plans for safety during the design phase. • Use the BIM model to identify leading edges, access and egress points, openings and skylights, elevator and mechanical shafts, loading and landing zones, and other related hazards. After these fall hazards are identified, we design in cast-in-place fall protection anchor points. • https://www.inthebigroom.com/2018/05/11/safety-construction-prevention-design/
New Zealand	Hamilton City Council Wastewater Treatment	• The 3D BIM model was used as a tool to run contractor safety inductions.

	Plants	
	Ara Institute of Canterbury Kahukura Block	• "Safety in design" was conducted along with BIM coordination

3.6 Drivers and barriers to adopting BIM for safety

A summary of drivers and barriers to adopting BIM for safety that were identified from the literature review is presented in Table 30.

Table 30 Drivers and barriers to adopting BIM for safety

Study	Country and region	Barriers	Drivers
(Enshassi et al., 2016)	Gaza strip	• Lack of BIM use • Insufficient training available • Not enough demand from client • Uncertainty of benefits • Lack of guidelines and standards • Lack of knowledge of safety engineering using BIM • High costs related to BIM software, hardware, and training • Lack of safety expertise of BIM users	/
(Marefat et al., 2019)	Iran	• Lack of in-house expertise • Lack of training • Lack of collaboration • No client demand • Unsure of the government's commitment to BIM cost	/
(Swallow & Zulu, 2019)	UK	• High costs • Time-consuming • Industry culture and resistance to change • Lack of awareness of 4D • Perception of value	• Reduce safety risk • Ability to foresee hazards • Improved project planning • Improved communication • Increased collaboration • Increased project visualisation
(Kiviniemi et al., 2011)	Finland	• Lack of safety object library • Limited 4D simulation for safety planning	/

4 Conclusions

This systematic review was aimed to investigate and understand the current status of BIM applications to construction health and safety and identify BIM4SAFETY best practices in the project lifecycle (i.e., design, procurement, and construction). The results showed that both research achievements and industry practices have significantly advanced BIM and related technologies for construction health and safety. Significant research achievements have been made in terms of formalised safety knowledge base, BIM-based rule-based checking, safety risk assessment, data-driven approaches, BIM-based safety planning, hazard identification, workspace planning, temporary structure, heavy equipment planning and operation, and BIM-based safety training and education. In addition, a number of important guidelines and standards were developed to support BIM for safety practices. These guidelines and standards defined standardized requirements, processes, and information flow, which promote the wide use of BIM for construction health and safety. In conclusion, BIM has been proven useful to digitalise construction health and safety in the whole project lifecycle. Previous research has demonstrated that it has significant potential to reduce accidents, although there is no direct evidence for the impacts. There is a clear trend that BIM has been increasingly used with other information technologies (e.g., sensors, VR, cloud computing, GIS, and UAV) to develop an information-rich digital twin of site safety. BIM is a useful tool and platform to provide relevant data, automate safety analysis, and visualise safety information. At the project level, these functions can enhance safety communication and collaboration and therefore improve the safety culture. Workers also benefit from the functions, as the real-time information improves workers' situation awareness and helps them make safe decisions in the highly dynamic construction site.

Despite these benefits, there are a number of significant barriers to the wider adoption of BIM for construction health and safety. First, all challenges of adopting BIM in general are applicable to specific BIM applications for construction health and safety. In addition, several unique barriers, like uncertain benefits of BIM for safety, lack of safety expertise of BIM users, being time-consuming, cannot be ignored.

5 Future research directions

The following research directions are recommended to promote future BIM applications to construction health and safety.

5.1 Safety object libraries

Future research and development efforts should be made to create a comprehensive safety object and component library to empower safety modelling within a BIM environment. This issue was mentioned in previous research (Sijie Zhang et al., 2015). A safety object can be defined as a digital description of products, equipment, or materials that are related to safety management. Examples include scaffolds, safety nets, anchorage systems, guardrail systems, passive and active fall protection systems, personal protection equipment, and so on. Although some health and safety information can be added to existing BIM objects, a comprehensive safety object library is needed to facilitate safety modelling, analysis, and simulation within a BIM environment. The safety object library can be a part of a national BIM object library, such as the one being developed by NBS in the UK (i.e., NBS National BIM Library).

5.2 A comprehensive computable safety knowledge base

Efforts have been made to develop a computable safety knowledge base for rule-based checking. However, these efforts are fragmented, and the knowledge bases and rule-based checking systems need to be tested in more complex construction projects. A systematic research effort is needed to develop a comprehensive computable knowledge base that supports identifying more hazards, particularly those that emerged from or were caused by spatial-temporal interactions among construction activities, equipment, and workers. Knowledge engineering tools such as ontology can be developed and utilized to enable semantic representation and reasoning. In addition, more research attention should be paid to other critical safety and health hazards like fall from ladder, fall through fragile material (e.g., skylight, old roof), electric shock, mobile elevating work platform issues, and health issues (e.g., fatigue and dust).

5.3 Standardized health and safety information structure

PAS 1192-6 requires that all stakeholders should use the same structure of risk information consistently and that all data entries should be editable, transformable, and traceable. However, there is a lack of a standardised health and safety information structure for the information cycle within the BIM environment. PAS 1192-6 does recommend using COBie and attaching health and safety information to the BIM model to facilitate the risk information cycle. However, more research is needed to develop a suitable data architecture that defines which and when health and safety data is collected and how it is stored, arranged, integrated, and put to use in a Common Data Environment (CDE). The data architecture should enable data mapping among different stakeholders (e.g., clients, designers, main contractors, subcontractors, and suppliers) when they exchange health and safety information. In addition, it should be noted that representing health and safety information using COBie does not enable automatic safety modelling and analysis. Model View Definitions are needed to support safety modelling and analysis in the BIM IFC model.

5.4 Evaluation by accident reduction

Past research has focused on the technical aspects of BIM applications for construction health and safety. Research that evaluates the impacts on safety performance in real projects has been limited. More evidence is needed regarding the mechanism by which the BIM applications prevent accidents. Future research should shed light on how BIM-based health and safety applications improve hazard management, shape workers' safety behaviour, and promote safety culture. The linkages between technical functions and accident causation processes (or accident prevention theories) should be strengthened. Any progress in this area can address the adoption barrier that industry practitioners are uncertain about the benefits of BIM-based site safety management applications.

5.5 BIM-based multi-stakeholder collaboration

As a lifecycle platform, BIM has significant potential to facilitate lifecycle multi-stakeholder collaboration on health and safety. However, there is no research conducted in this area. Aspects that warrant future research include the effects of client leadership, multi-stakeholder collaboration workflow, and barriers and drivers to the lifecycle approach. Note that the Health and Safety at Work Act 2015 (HSWA) requires that a PCBU (person conducting a business or undertaking) actively engage with and enable the participation and representation of workers. Previous research made an attempt to facilitate one-way risk communication towards workers using BIM. Future efforts can be made to form a feedback loop by allowing workers to raise concerns, report incidents, and contribute to decision making.

5.6 Integrating health and safety into NZ BIM Handbook

NZ BIM Acceleration Committee published the third edition of The New Zealand BIM Handbook in 2019. The Handbook defines client information requirements, typical BIM workflow, and modelling and documentation practice. However, health and safety are not included in the BIM Handbook. Future efforts are needed to develop NZ BIM-based health and safety guidelines and standards based on The New Zealand BIM Handbook.

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Appendix A

BIM functionalities again site safety aspect matrix (Part 1)		BIM functionality			
		V1	**V2**	**V3**	**V4**
Site safety management aspects	**H1, H2, H3, H4, H19**	(Choe & Leite, 2017; Ding et al., 2016; Wang et al., 2015; S. Zhang et al., 2013)		(Li et al., 2021; Tran et al., 2021)	
	H5	(Golparvar-Fard et al., 2011; Hilfert et al., 2016; Pereira et al., 2018)	(Li, Lu, Chan, et al., 2015)	(Getuli, Capone, & Bruttini, 2021; Golparvar-Fard et al., 2011)	
	H6	(Getuli et al., 2017; Golovina et al., 2016; Melzner, Zhang, et al., 2013; S. Zhang et al., 2013)	(AlSaggaf & Jrade, 2021; Choe & Leite, 2017; Shang & Shen, 2016; Tran et al., 2021)	(AlSaggaf & Jrade, 2021; Choe & Leite, 2017; Shang & Shen, 2016; Tran et al., 2021)	
	H7, H14, H15, H16, H17, H18	(Collins et al., 2014; Ding et al., 2016; Le & Hsiung, 2014; Wu et al., 2015; Zou et al., 2016)	(Lee et al., 2019)	(Hosseini & Maghrebi, 2021; A. H. Liu et al., 2021; Shang & Shen, 2016; Zou et al., 2016)	
	H8, H10	(Arslan et al., 2019a; Arslan et al., 2014; Cheung et al., 2018; Y. Fang et al., 2016; Riaz et al., 2014; Riaz et al., 2017; Wu et al., 2015)		(Alizadehsalehi et al., 2020; Golparvar-Fard et al., 2011; Tak et al., 2021)	(Fan et al., 2021; Tian et al., 2021)
	H9	(Hosseini & Maghrebi, 2021; Kim & Lee, 2019; Marzouk & Daour, 2018)		(Hosseini & Maghrebi, 2021; Kim & Lee, 2019; Marzouk & Daour, 2018)	
	H11	(Collins et al., 2014)	(Kim et al., 2018b)	(Kim et al., 2018a; K. Kim et al., 2016; Kim et al., 2018b)	
	H12	(Marzouk & Abubakr, 2016)			
	H13	(Arslan et al., 2019b; Choe & Leite, 2017; Golovina et al., 2016; Khan et al., 2021; H. Moon et al., 2014; Yi et al., 2015)	(Lee et al., 2019)	(Choe & Leite, 2017; K. Kim et al., 2016; HyounSeok Moon et al., 2014; H. Moon et al., 2014; Tak et al., 2021; Tran et al., 2021; S. Zhang, J. Teizer, N. Pradhananga, et al., 2015)	(Fan et al., 2021)
	F1	(Dong et al., 2018; Li, Lu, Hsu, et al., 2015)	(Dong et al., 2018; Li, Lu, Hsu, et al., 2015)		

BIM functionalities again site safety aspect matrix (Part 2)		BIM functionality						
		A1	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**
Site safety management aspects	**H1, H2, H3, H4, H19**			(Tran et al., 2021)	(K. Kim et al., 2016)			
	H5							
	H6		(Melzner, Zhang, et al., 2013)	(AlSaggaf & Jrade, 2021; Marzouk & Abubakr, 2016; Shang & Shen, 2016; Tran et al., 2021; S. Zhang, J. Teizer, & N. Pradhananga, 2015; S. Zhang, J. Teizer, N. Pradhananga, et al., 2015)			(Choe & Leite, 2017)	
	H7, H14, H15, H16, H17, H18	(Lee et al., 2019)		(A. H. Liu et al., 2021; Shang & Shen, 2016)		(Z. Liu et al., 2021)		
	H8, H10			(Tak et al., 2021; Tian et al., 2021)	(D. Liu et al., 2020)			(Park et al., 2017; Riaz et al., 2014)
	H9							
	H11		(Kim et al., 2018a)		(K. Kim et al., 2016)			
	H12			(Chen et al., 2011; Marzouk & Abubakr, 2016)				
	H13	(Lee et al., 2019)	(Melzner, Zhang, et al., 2013)	(Chavada et al., 2012; Choi et al., 2014; HyounSeok Moon et al., 2014; Tak et al., 2021; Tran et al., 2021; Zhang & Hu, 2011; S. Zhang, J. Teizer, N. Pradhananga, et al., 2015)	(K. Kim et al., 2016; D. Liu et al., 2020)		(Choe & Leite, 2017; HyounSeok Moon et al., 2014)	
	F1							

BIM functionalities again site safety aspect matrix (Part 3)		BIM functionality
		D1 and D2
Site safety management aspects	**H1, H2, H3, H4, H19**	(Ding et al., 2016; Hossain & Ahmed, 2019; Kim et al., 2015; Li et al., 2021; M. Li, H. Yu, H. Jin, et al., 2018; M. Li, H. Yu, & P. Liu, 2018; Mihić et al., 2018; Park & Kim, 2013; A. J. P. Tixier et al., 2017; Tran et al., 2021; Zhang & Hu, 2011; Zhang et al., 2016; S. Zhang, F. Boukamp, et al., 2015; S. Zhang et al., 2013)
	H5	(Afzal & Shafiq, 2021; Getuli, Capone, & Bruttini, 2021; Getuli, Capone, Bruttini, et al., 2021; Golparvar-Fard et al., 2011; Hilfert et al., 2016; Li, Lu, Chan, et al., 2015; Park & Kim, 2013; Pereira et al., 2018)
	H6	(Bansal, 2011; Chavada et al., 2012; Y. Fang et al., 2016; Getuli et al., 2017; Golovina et al., 2016; Golparvar-Fard et al., 2011; H. Kim et al., 2016; K. Kim et al., 2016; M. Li, H. Yu, & P. Liu, 2018; Melzner, Zhang, et al., 2013; HyounSeok Moon et al., 2014; Park & Kim, 2013; Park et al., 2017; Pham et al., 2020; Schwabe et al., 2019; Wang et al., 2015; Zhang et al., 2016; S. Zhang et al., 2013; S. Zhang, J. Teizer, N. Pradhananga, et al., 2015)
	H7, H14, H15, H16, H17, H18	(Collins et al., 2014; Ding et al., 2016; Hosseini & Maghrebi, 2021; Kim et al., 2020; Le & Hsiung, 2014; Lee et al., 2019; M. Li, H. Yu, H. Jin, et al., 2018; Lin et al., 2017; A. H. Liu et al., 2021; Z. Liu et al., 2021; Luo & Gong, 2015; Wu et al., 2015; Xu & Wang, 2020; Zhang et al., 2021)
	H8, H10	(Alizadehsalehi et al., 2020; Arslan et al., 2014; Cheung et al., 2018; Collins et al., 2014; Costin et al., 2015; Dong et al., 2018; Fan et al., 2021; Y. Fang et al., 2016; Golovina et al., 2019; Golparvar-Fard et al., 2011; Guo et al., 2014; Hasan et al., 2021; Liang et al., 2018; Lin et al., 2017; D. Liu et al., 2020; Park & Kim, 2013; Park et al., 2017; Riaz et al., 2014; Riaz et al., 2017; Tak et al., 2021; Tian et al., 2021; Wu et al., 2015; Xu & Wang, 2020)
	H9	(Deng et al., 2019; Getuli, Capone, Bruttini, et al., 2021; Hosseini & Maghrebi, 2021; Kim & Lee, 2019; Marzouk & Daour, 2018)
	H11	(Kim et al., 2018a; K. Kim et al., 2016; Kim et al., 2018b)
	H12	(Chen et al., 2011; Marzouk & Abubakr, 2016)
	H13	(Arslan et al., 2019b; Astour & Franz, 2014; Bansal, 2011; Chavada et al., 2012; Choe & Leite, 2017; Choi et al., 2014; Fan et al., 2021; Y. Fang et al., 2016; Getuli et al., 2020; Golovina et al., 2016; H. Kim et al., 2016; K. Kim et al., 2016; Lee et al., 2019; D. Liu et al., 2020; Melzner, Zhang, et al., 2013; HyounSeok Moon et al., 2014; H. Moon et al., 2014; Pham et al., 2020; Schwabe et al., 2019; Tak et al., 2021; Tran et al., 2021; Zhang & Hu, 2011; S. Zhang et al., 2013; S. Zhang, J. Teizer, & N. Pradhananga, 2015; S. Zhang, J. Teizer, N. Pradhananga, et al., 2015)
	F1	(Dong et al., 2018; Guo et al., 2014)

Appendix B

Key achievements in BIM-based construction health and safety management

Site safety aspects	Key study	Achievements
Safety planning	(S. Zhang et al., 2013)	• Developed a BIM-based automatic safety checking system • Able to identify hazards and provide control measures • Focused on fall from height (limitation)
	(Melzner, Teizer, et al., 2013)	• Applied the BIM-based automatic safety checking system based on both the USA and Germany fall protection regulations
	(Getuli et al., 2017)	• Developed a rule-checking system to support construction site layouts and safety planning • Object tables have been created for each construction site element
	(Schwabe et al., 2019)	• Developed a model-based rule checking for the planning of construction site layouts. • Drools with the Industry Foundation Classes (IFC) to retrieve data from a building information model and use the information within the rule engine
	(Wang et al., 2015)	• Combine point-cloud and BIM for safety equipment planning by identify fall hazards
	(M. Li, H. Yu, & P. Liu, 2018)	• BIM-based risk identification system for underground construction • SQL database and Backus–Naur form are used to express the safety risk knowledge,
Hazard management	(S. Zhang, F. Boukamp, et al., 2015)	• Able to automate hazard identification and identifying solution based on BIM • Ontology-based • Limited to fall from height. Issues related to layout, struck-by, proximity, cave-in were not considered.
	(Ding et al., 2016)	• Ontology-based risk assessment systems • Risk information is linked with each BIM element • semantic representation of risk knowledge, hard to maintain • At present, the prototype only contains the typical construction technical risk knowledge for the deep foundation pit excavation engineering.
	(Park & Kim, 2013)	• Developed a prototype system that integrates BIM-based safety planning, inspection, and training modules. • Evaluated based on interviews with workers and managers
	(Zhang et al., 2016)	• BIM-based risk assessment system for tunnelling
	(A. J. P. Tixier et al., 2017)	• Safety clash and hazardous scenarios detection based on data mining techniques
	(M. Li, H. Yu, H. Jin, et al., 2018)	• BIM-based risk identification system for metro construction
	(Kim et al., 2015)	• Developed a BIM-based similar past accident retrieval system • Validated by precision and recall
	(Mihić et al., 2018)	• Developed a construction hazard database • Hazards grouped and connected with construction activities • 115 hazards
	(Tran et al., 2021)	• Developed a system that can identify hazards caused by spatial-temporal relations between activities • The developed prototype is based on the analysis of 496 accident reports • Not address re-scheduling or schedule optimisation based on hazards
Risk assessment	(Ding et al., 2016)	• Created a risk map methodology based on BIM, ontology and semantic web technology. • Can semantically inferred interdependences between risks and risk paths. • The richness of the knowledgebase is limited to deep foundation pit excavation engineering.
	(Zou et al., 2016)	• Developed a customized Risk Breakdown Structure (RBS) that aims to bridge the knowledge gap between risk information and BIM.

Site safety aspects	Key study	Achievements
		• Poor performance in quantitative risk analysis. • The scope limited to bridge projects. • The system effectiveness in practice was not validated.
	(Wu et al., 2015)	• A BIM-based monitoring system with a complete monitoring view was established. • Complex engineering monitoring information can be visualized and communicated efficiently. • The application area limited to urban deep excavation projects.
	(Shang & Shen, 2016)	• Established a 4D (3D model and schedule) BIM-based temporal-spatial construction safety assessment methodology. • The job site collisions can be detected, visualized, and analysed. • Contextual information about on-site objects and environments (beyond spatial-temporal information) were not thoroughgoing.
	(A. H. Liu et al., 2021)	• A 4D GeoBIM (integration of Geospatial (Geo), BIM, and project schedule information) system was proposed. • Enhance data interoperability between practical site data and other data sources. • Focus on commercial infrastructure project. • The standardization of semantic mapping between BIM and GIS remain undeveloped.
Safety training/education	(Park & Kim, 2013)	• Established a novel safety management and visualization system (SMVS) that integrates BIM, location tracking, augmented reality (AR), and game technologies. • Capable to improve the identification of field safety risks, increase the risk recognition capacity of workers, and enhance the real-time communication between construction manager and workers. • The real-site safety management performance such as accident prevention rate, time cost, and cost–benefit balance remains unclear.
	(Li, Lu, Chan, et al., 2015)	• Developed a Proactive Construction Management System (PCMS) merge Unity3D-based data visualisation technology, BIM, and Chirp-Spread-Spectrum-based (CSS) real-time location technology. • Able to conduct real-time construction elements tracking and post-event visualisation analysis for off-site safety training. • Can only perform location-related hazards identification. • The actual mechanism of the realistic real-time data visualisation remain vague.
	(Hilfert et al., 2016)	• A realistic VR platform was developed by head-mounted displays corroborate with Unreal Engine 4. • The early hazard recognition, workers' situational awareness, safety behaviour of labours near heavy equipment, and stakeholder's hazard evaluation skill can be improved. • Cost-benefit balance and motion sickness.
	(Pereira et al., 2018)	• A novel safety-related knowledge and conditions visualization methodology and a virtual data-rich safety training platform was developed based on BIM and panoramic augmented reality technique. • The hazard perception skill can be enhanced by 360-degree panoramas. • Focus on fall hazards (ladders, floor openings, personal arresting gear, and unprotected edges). • Its capability for real labour remain unclear.
	(Getuli, Capone, & Bruttini, 2021)	• Created a BIM and VR-based standardized protocol. • The safety training standardization can be promoted. • Current applicable methods and metrics are insufficient for safety-related experiences collection and evaluation.
Emergency response	(Marzouk & Daour, 2018)	• A BIM-based multiple construction methods-enabled worker evacuation process simulation methodology was proposed. • Construction sites labour evacuation plan can be automated simulated based on different construction methods.

Site safety aspects	Key study	Achievements
		• Static BIM models are difficult to provide sufficiently convincing dynamic construction site simulations.
	(Kim & Lee, 2019)	• Construction daily evacuation paths can be automatic generated. • Static BIM models are difficult to provide sufficiently convincing dynamic construction site simulations.
	(Hosseini & Maghrebi, 2021)	• The fire emergency occurrence risk and evacuation performance associated risks can be analysed. • The analysis results largely relay on manual inputs.
Temporary structure	(K. Kim et al., 2016)	• Developed a BIM-based automated safety checking algorithms and a safety planning platform. • Based on simulation, temporary structure-related safety hazards can be identified automatically. • Focused on hazards associated with crews spatial movements on scaffolding.
	(Collins et al., 2014)	• Scaffoldings project safety risk levels can be visualized. the mitigation suggestions will be proposed. • Focusing on masonry wall construction using scaffolding.
	(Kim et al., 2018a)	• Multiple scaffolding plans can be automatically generated. • Safety, cost, and duration can be quantitatively evaluated. • Lack on standardization on hazard weighting.
	(Kim et al., 2018b)	• Multiple scaffolding plans can be automatically generated. • Safety, cost, and duration can be quantitatively evaluated. • Manual constructability checking are required.
Heavy equipment management	(Marzouk & Abubakr, 2016)	• A genetic algorithms-based decision support system was developed to determine types and locations of tower cranes in a construction site. • Week on facing dynamic nature of construction sites.
	(Chen et al., 2011)	• Established an augmented reality (AR)-based integrated crane operation enhancement system. • Increase crane operators cognitive load.

Key achievements in site safety inspection and monitoring

Study	Sensor integrated with BIM	Monitoring what	Achievement
(Park et al., 2017)	Bluetooth low-energy (BLE)-based location sensor	workers' location	Can real-time worker location information is mapped with pre-defined hazardous areas on BIM
(Yihai Fang et al., 2016)	RFID	workers' location	Visualize worker's location on BIM
(Riaz et al., 2014)	Wireless sensors	temperature/oxygen level monitor confined space	to monitor construction workers in confined spaces
(Cheung et al., 2018)	Wireless sensors	hazardous gas level and environmental conditions (e.g., temperature and humidity)	The prototype system visualise the conditions on BIM in different colours. It also can alarm and activate the ventilator on-site to remove the hazardous gases.
(Arslan et al., 2019a)	Bluetooth Low Energy (BLE) beacons	the trajectories of workers	WoTAS could help understand workers and machinery movement and contribute to accident reduction.

Study	Sensor integrated with BIM	Monitoring what	Achievement
(Ding Liu et al., 2020)	indoor positioning and inertial measurement unit	worker’s conditions (e.g., position, walking speed, and facing direction).	The information was then fed into the BIM 3D model to identify if the worker is in a danger zone, closed to the roof edge, and in other dangerous situations. The system is able to generate real-time warnings to improve the worker’s situation awareness.
(Alizadehsalehi et al., 2020)	UAV	the location of potential hazards	The information is then integrated into BIM to facilitate visualization and communication.

Appendix C Reviewed papers

44 articles for BIM-based design for safety

Aslam Hossain, M. D., Abbott, E. L. S., & Chua, D. K. H. (2017). Design for safety knowledge-based bim-integrated risk register system. 9th International Structural Engineering and Construction Conference: Resilient Structures and Sustainable Construction, ISEC 2017,

Brice, R., Dalasung, E., & Joshi, S. (2019). Changi water reclamation plant: The plant of the future constructed in the now. 92nd Annual Water Environment Federation's Technical Exhibition and Conference, WEFTEC 2019,

Duncheva, T., BuHamdan, S., Hairstans, R., & Al-Hussein, M. (2018). BIM-enabled health & safety analysis of cross laminated timber onsite assembly process. 17th International Conference on Modeling and Applied Simulation, MAS 2018,

Essawy, Y. A. S., & Nassar, K. (2017). BIM-Based model for the automatic generation of construction sequences. 24th EG-ICE International Workshop on Intelligent Computing in Engineering 2017,

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Kamardeen, I. (2010). 8D BIM modelling tool for accident prevention through design. 26th Annual Conference of the Association of Researchers in Construction Management, ARCOM 2010, Leeds.

Kasirossafar, M., Ardeshir, A., & Shahandashti, R. L. (2012). Developing the sustainable design with PtD using 3D/4D BIM tools. World Environmental and Water Resources Congress 2012: Crossing Boundaries, Albuquerque, NM.

Kasirossafar, M., & Shahbodaghlou, F. (2013a). Application of visualization technologies to design for safety concept. 6th Congress on Forensic Engineering 2012: Gateway to a Better Tomorrow, San Francisco, CA.

Kasirossafar, M., & Shahbodaghlou, F. (2013b). Building information modeling or construction safety planning. 2nd Annual International Conference Sustainable Design, Engineering and Construction, ICSDEC 2012, Fort Worth, TX.

Kim, I., Lee, Y., & Choi, J. (2020). BIM-based hazard recognition and evaluation methodology for automating construction site risk assessment [Article]. *Applied Sciences (Switzerland)*, *10*(7), Article 2335. https://doi.org/10.3390/app10072335

Lee, Y., Kim, I., & Choi, J. (2020). Development of BIM-based risk rating estimation automation and a design-for-safety review system [Article]. *Applied Sciences (Switzerland)*, *10*(11), Article 3902. https://doi.org/10.3390/app10113902

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Park, H., Lee, S., Kim, E., & Choo, S. (2017). A Proposal for building safety diagnosis processes using bim-based reverse engineering technology. 22nd International Conference on Computer-Aided Architectural Design Research in Asia: Protocols, Flows and Glitches, CAADRIA 2017,

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1 article for BIM4Safety during procurement

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Industry. World Multidisciplinary Civil Engineering-Architecture-Urban Planning Symposium, WMCAUS 2016,

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