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BIM-based construction safety risk library

William H. Collinge *, Karim Farghaly, Mojgan Hadi Mosleh, Patrick Manu, Clara Man Cheung, Carlos A. Osorio-Sandoval

Department of Mechanical, Aerospace and Civil Engineering, School of Engineering, The University of Manchester, M13 9PL Manchester, United Kingdom

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ABSTRACT

This paper presents a digital tool and Safety Risk library to assist designers in their health and safety work in BIM digital environments. Addressing an industry need for improved knowledge sharing and collaboration, the BIM Safety Risk library tool aligns with a Prevention through Design (PtD) approach that links safety risks to treatments via different risk scenarios. Motivated by continuing sub-optimal health and safety management processes, the research employs a conceptual framework rooted in construction guidance: structuring data via a 7-stage ontology to improve designer knowledge of issues and give access to an expanding safety knowledge base (the BIM Safety Risk Library). The tool facilitates tacit and explicit knowledge sharing in visual environments, enabling the construction industry to benefit from their health and safety data while providing an interactive learning tool for designers. The structuring of data also opens up possibilities for other digital advances (e.g. via automatic rule checking).

1. Introduction

Construction work continues to be hazardous due to its working environments and the high risks involved. In the United Kingdom (UK) alone, the construction industry accounts for about 61,000 non-fatal work-related injuries [1]. From a fatality perspective, construction accounted for 40 fatal injuries to workers in 2019/20; the cost of occupational injuries and new cases of occupational ill health being estimated at £1.2 billion [1]. Whilst improving safety can broadly be divided into the pre-construction and in-construction phase [2], it is acknowledged that pre-construction approaches can reduce risks involved in construction, operation and maintenance: many accidents being predictable and preventable during design, if appropriate approaches, tools and technologies are utilized [3–5]. Designers can therefore play a significant role in accident reduction [6]. Meanwhile, construction regulations in several countries have integrated safety management into construction planning and design work (e.g. the Construction Design and Management (CDM) 2015 regulations in the UK). As a result, safety management is no longer the sole responsibility of contractors during construction, but is also the responsibility of client and designer; pre-construction risk identification helping contractors prepare for risks well before commencing their work [7]. Such an approach also helps avoid delays by assisting in the identification and preparation work needed for particular risks during construction and operation [8]. The digital transformation of construction requires researchers to develop interoperable and integrated ICT tools to improve project management processes [9]. Health and safety are part of that trajectory of research work. The process necessitates a rationalisation and optimization of the health and safety risk identification and treatment process.

The recognition that designers can play a major role in reducing construction health and safety risks has led to a Prevention through Design (PtD) approach; also known as ‘safety in design’ (SiD), and ‘design for construction safety’ (DfS) [10,11]. Effective PtD enables and facilitates the identification of risks and treatments by designers; PtD being an important part of a holistic approach to minimizing risks and enhancing worker safety in the process [12]. Whilst the majority of designers need ongoing construction safety training, the importance of digital tools for addressing safety issues has also been recognised [13,14]. However, despite the global growth of information communication technologies (ICT), such as building information modelling (BIM) [15], the use of ICT for better health and safety management remains limited; its` full potential is yet to be realised [16,17]. Specifically, designers need to be provided with mitigations and treatments for

* Corresponding author.
E-mail addresses: william.collinge@manchester.ac.uk (W.H. Collinge), karim.farghaly@ucl.ac.uk (K. Farghaly), mojgan.hadimosleh@manchester.ac.uk (M.H. Mosleh), patrick.manu@manchester.ac.uk (P. Manu), clara.cheung@manchester.ac.uk (C.M. Cheung), carlos.osorio@nottingham.ac.uk (C.A. Osorio-Sandoval).

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identifiable risks in digital design environments. Such a system necessitates access to a comprehensive safety management system (SMS): an SMS consisting of a knowledge base that provides information to enhance the competence and ability of designers to visualize risks and identify remedies for harmful events by reducing the consequences and/or providing proper treatment plans. These issues provided the motivation for the research reported in this paper: work which resulted in the development of a prototype digital risk suggestion tool for construction designers to connect with the archive of health and safety information relevant for their work, called the BIM Safety Risk Library for Construction.

The BIM Safety Risk Library aims to make the data-rich archive of the UK Health and Safety regulator (i.e. Health and Safety Executive - HSE) accessible and useable to industry in BIM and non-BIM enabled projects. As reported in the paper, the research team employed an ontological approach to structure both explicit and tacit data in a digital environment (through both interactive tool and knowledge base): ontologies provide a common conceptualisation of a domain on which different parties agree [18]. The ontology is rooted in HSE datasets, facilitating the practical implementation of a PtD approach through an accessible knowledge-based system in a BIM environment. As detailed in the methodology, this work consisted of a literature review, software package research, industry consultations, ontology development, industry workshops, software interface development and prototype rollout and testing.

Practically, the research mobilises the standard industry guidelines for management of construction health and safety management: the Construction (Design and Management) Regulations (i.e. CDM 2015) [19] into a digital environment and realises many of the stated objectives within PAS 1192:6 Specification for collaborative sharing and use of structured Health and Safety information using BIM [20] through the digital tool and BIM Safety Risk library.

Theoretically, the creation of an ontology that facilitates the structuring of health and safety data and human knowledge (both tacit and explicit) provides a foundation for further digital technology developments such as automatic rule checking via IFC classes and other technological developments such as internet of things (IoT), big data, advanced manufacturing, robotics, 3D printing, blockchain technologies and artificial intelligence (AI), as recognised by the award of a buildingSMART 2020 prize [21].

The tangible value of the tool and accompanying Safety Risk library resides in linking potential risks with treatments in a visual, interactive digital environment that facilitates communication, collaboration and a sharing of knowledge, ideas and suggestions between practitioners at multiple stages of the construction project lifecycle. Capturing risk scenarios and treatments in a structured way lays the groundwork for mobilization of the HSE archive of construction health and safety risk data to a BIM-environment, and opens up the opportunity for companies to mobilise risks/treatments from previous projects for current use. The tool can also be both a learning and training tool for designers.

The paper begins with a literature review of Safety in Design (SiD) technologies that highlights an ongoing industry need for designer access to health and safety knowledge in BIM environments. A methodology section describes the empirical research and tool development processes undertaken: development of a risk scenario and treatment ontology (including seven concepts and sub-concepts), a treatment matrix based on treatment prompt type and project stage of implementation and creation of a CSV (comma separated values) file including nine scenarios and 162 treatment prompts related to fall from open/edge and in-situ concrete buildings. A participatory action research (PAR) approach with industry led to the development and rollout of a BIM prototype tool (new version of SafetiBase in 3D Repo), enabling designers to identify potential risks and provide appropriate treatment based on the developed CSV file. Further sections describe how the tool is being piloted by industry, further work planned and a discussion of the tool in practical and theoretical terms. A conclusions section draws the insights of the paper together, highlighting the fact that recent implementations of cross domain building information using semantic web technologies have shown great success in the AEC sector [22]; the BIM Safety Risk library making a positive contribution to the digitisation of construction health and safety work.

2. Safety in design (SiD) tools and technologies

The development and use of digital tools to improve construction safety is an important stream of research. Whilst Damnjanovic and Reinschmidt [23] note that risk identification should be an ongoing process throughout the project life cycle, technologies now offer new opportunities for multiple stakeholder engagement around shared digital models. Whilst several recent studies review BIM and its application to safety during construction work (e.g. [16,24]), this review focuses upon design phase tools and technologies, pivoting around Safety in Design (SiD), also known as Prevention through Design (PtD).

Whilst technologies continue to evolve for improving worker safety and well-being, such as the workforce sustainability tool of Karakhan et al. [25] and the decision-making tool of Nnaji et al. [26], knowledge bases of data can still provide the foundational dataset of information for multiple applications. In construction, such health and safety knowledge bases can provide information to enhance the PtD competence of designers, but such libraries need to embrace both tacit expert knowledge as well as explicit regulations and guidelines in open, accessible and functional ways that align to working practices [27]. Additionally, such knowledge bases should be designed to enable future technologies to connect to their datasets, thus strengthening the application and enhancing interoperability. In reviewing the literature related to SiD tools and technologies, the role of knowledge bases and the ontologies upon which they are built, needs to be contextualized with how designers currently approach and understand PtD.

Morrow et al. [28] classified designers' views towards PtD as falling into three different perspectives: a) designers who do not address safety issues at all due to lack of knowledge; b) designers that seek specialist advice to eliminate or highlight risks on designs; and c) designers who are knowledgeable about risks and take responsibility towards their prevention. Whilst any digitally based PtD system should provide these different perspectives, it should ultimately aim to eliminate or reduce risks by providing designers with the knowledge needed to treat or mitigate a risk identifiable in a design model. Hardison and Hallowell [29] recognised this issue in their review of future PtD research directions, noting the need for improving hazard recognition during design phase work using knowledge resources and technological platforms. Their review of twelve research studies into designer recognition skills with BIM safety applications highlighted that only six tools provided safety suggestions, whilst none of the systems allowed for objective evaluation of safety risk levels of design attributes, elements or potential safety solutions. Other scholars have made similar insights. For example, Jin et al. [30] pointed out that implementation of PtD is usually inhibited due to designers' lack of knowledge about construction safety and a limitation in design-for-safety tools and procedures available on the market for designers to use. In line with this view, Vassie et al. [31] urged that a PtD system should provide information, tools and techniques to enhance the PtD competence of designers and planners. The value of visualizing risks in a digital environment has also been duly noted and emphasized by many academics, including Golabchi et al. [5] regarding ergonomics and labour issues on construction projects and Rodrigues et al. [32] in their work regarding BIM-based tools and occupational risk prevention measures. Therefore, there remains a need to provide designers with the knowledge to assist in their work, providing objective evaluations of safety risks and suggestions for treatments in the process. It can be argued that important opportunities reside in the mobilization of health and safety knowledge for designers in BIM environments and proper visualization/access techniques to that knowledge.

The principal components of a PtD system are illustrated in Fig. 1. The figure shows a hazard identification component whereby data from industry standards and safety incidents assist in risk identification; a rules/relationships component for risk/mitigation definition from the data structured via ontology/ontologies, and an application component (e.g. BIM, virtual reality) that enables designers to access and use information in design models for risk identification and treatment suggestion.

Whilst academics have engaged with these components of a PtD system differently, a central issue is the knowledge base of health and safety data (e.g. incidents, reports, mitigations) from which hazards and treatments may be drawn. In construction, knowledge bases can be created and managed by individual companies or by governmental bodies (e.g. the Health and Safety Executive: HSE) that oversee health and safety activities.

Ideally, knowledge bases should provide information to enhance the competence of designers and planners whilst also facilitating input from individuals with sufficient knowledge in construction health and safety. Such combinations of explicit and tacit knowledge [33] must be presentable and useable (via effective collation, filtering, comparison and analysis) to practitioners; such work needs to follow logical industry-standard processes wherever possible. The industry standard specification for the collaborative sharing and use of health and safety information using BIM: PAS 1192:62018 [20], gives guidance that looks forward to future digital applications and what academia and industry should be aiming to achieve. For example, the risk information delivery cycle from PAS 1192:6 [20] (Fig. 2), highlights identification, use and sharing of risk information as important, noting a number of concepts/issues to be addressed in applications. These issues align well with the principal components of a PtD system (Fig. 1); identification of hazards; data evaluation and sharing and use of information by practitioners. Whilst the specification PAS 1192:6 [20] is now undergoing evaluation and conversion to an ISO 19650 standard (for possible completion by 2024), it remains an important foundational document and template for systems engineering developments in the area of BIM and health and safety technology management. The PtD tool and library reported in this paper followed principles and guidance of the industry PAS 1192:6 [20] standard closely.

The difference between explicit and tacit knowledge in the context of construction health and safety is an important one that needs to be emphasized, especially with reference to the design and development of digital technologies. Explicit knowledge is formulated and codified in corporate procedures and best practices [27], whilst tacit knowledge is tied to individual skills and perceptions, often being applied unconsciously in project contexts. In safety management, explicit knowledge resides in sources such as accident records, safety regulations and guidelines [34], in documents like RIDDORs (Reporting of Injuries, Diseases and Dangerous Occurrences Regulations) and press releases, but also in recordings of near miss accident events that disrupt the project workflow and generate economic losses [35]. Tacit knowledge mainly derives from safety hazard recognition from designers' experience, and is more difficult to capture. An optimal PtD system would embrace both explicit and tacit knowledge [8,36–38], providing further use. Previous research to develop knowledge systems has embraced both explicit and domain knowledge [8,36–38], and the tool described in this paper also embraces both explicit knowledge (i.e. from sources such as RIDDORs and press releases) and tacit knowledge (captured via industry workshops), as detailed in the paper. Previous work concerning safety knowledge systems development has revolved around four main areas: 1) knowledge acquisition; 2) knowledge management; 3) software application development; and 4) expert systems/artificial intelligence (AI).

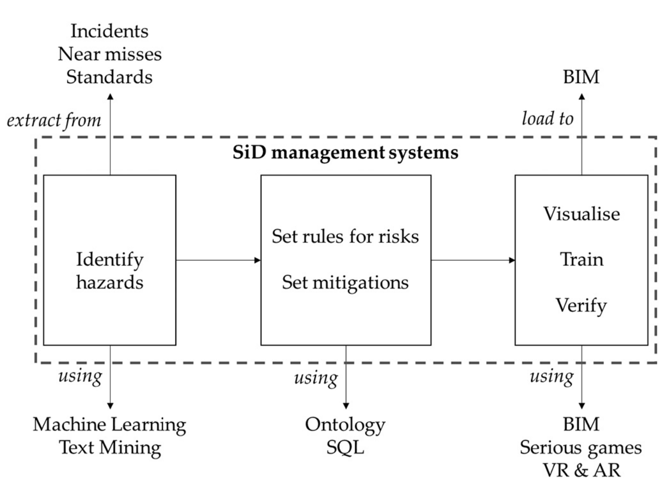

Fig. 1. Principal components of PtD systems.

2.1. Knowledge acquisition

Knowledge acquisition is a key process for the creation of any knowledge base that aims to be comprehensive and complete, knowledge acquisition connecting with the hazard identification component of a PtD system (Fig. 1). Effective knowledge acquisition systems should aim to improve the ill-structured stored information related to safety risks by collecting and clustering information into ordered formats to facilitate easier analysis. In the early days of PtD implementation, Wang and Ruxton [39] proposed a bottom-up method to improve safety identification especially in projects with insufficient safety data. Based on such a method, Total-Safety [40] and the DFSP tool [34] were developed to help engineers produce construction method statements with high levels of hazard identification. Hossain et al. [8] developed a Design for Safety (DfS) knowledge library structured into a 6-level hierarchical ontology to better capture the safety knowledge. Their ontology starts with the design topic, followed by the design element, work activity, constraint, safety risks and finally DfS required design features. Other systems have also been developed to identify possible safety hazards and accident precautions [41], environmental and human risk factors [42], and near-miss information [35]. These systems pivot on agreed taxonomies for structuring data related to health and safety risks, and the tool described herein is similarly organized, using a risk scenario/treatment ontology for structuring the data (Fig. 4). Identifying, extracting and transforming information from knowledge sources into machine readable formats is likely to require data mining, statistical analysis or even manual annotation techniques. However, if the process is effective, information may then be utilized by designers and planners in different software applications for activities such as visualization, safety training and automatic rule checking.

2.2. Knowledge management

Regarding knowledge management, scholars have endeavoured to bring the ontology concept to the construction safety domain. An ontological approach offers a way to integrate and map different datasets from different sources and potentially enhance collaboration between different stakeholders responsible for better construction safety. As Falquet et al. [18] noted, although ontology engineering has grown as a discipline in multiple fields, the practical implementation of ontologies in specific application contexts remains a challenging task. Therefore, the link between databases and ontologies still requires focused research and development work [18].

From a very general perspective, an ontology is an explicit specification of some conceptualization of a domain [43]. A conceptualization is an abstract model that represents the entities of a domain in terms of concepts, relations, and other modelling primitives. In principle, the specification of this conceptualization could take any form. However, the most commonly used ontological languages specify the meaning of

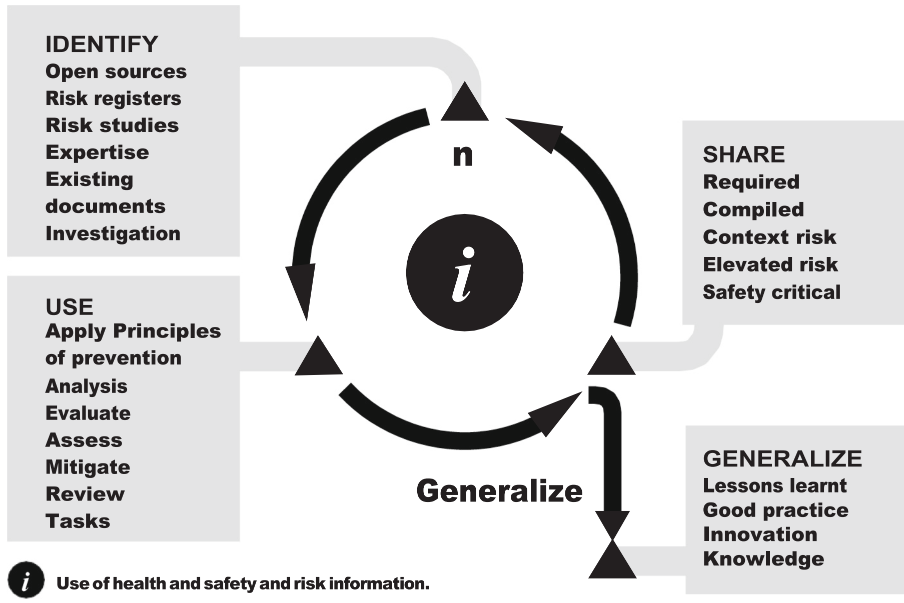

Fig. 2. Risk information cycle, from PAS 1192–62,018 [20].

concepts with some form of explicit definition. Thus, an ontology comprises a representational vocabulary with different types of symbols (class names, relation names, etc.); a set of definitions that specify the meaning of the vocabulary [18].

Based on the conceptualisation definition of ontology, more researchers defined ontology in computer science and added further requirements to enable automated reasoning. Borst [44] added two requirements to the definition of ontology: formal, which means that the ontology is written in a machine language where it is easily processed, and sharable, which means that the ontology is developed based on an agreement between experts in the knowledge domain. Both requirements could guarantee the usage of the ontology in different applications.

The application of ontologies and Linked Data has enjoyed great popularity in domains, including biology, medical records, cultural heritage, accounting, and social media [45]. These success stories encourage the implementation of ontologies and Linked Data in the Architecture, Engineering, Construction and Operation (AECO) domain [46]. The linked Data based approach is one of the most common approaches for publishing the ontologies by construction researchers as the machines can easily interpret them [47].

As noted by Ding et al. [36], an effective ontology can improve model flexibility and extendibility, provide a robust semantic representation, and enhance knowledge retrieval by improving the retrieval requests from the concept level. Several ontologies proposed in the literature address safety information sharing and job hazards. For instance, Zhang et al. [48] developed an ontology for job hazard analysis for improving construction safety knowledge management in BIM environments. Their particular ontology provides a potential link between safety risk knowledge and the BIM elements by mapping the developed ontology classes with IfcOwl classes. Other scholars have conducted similar work. For example, Ding et al. [36] linked risk knowledge with related building objects in a BIM environment using ontology based methodology; Ding et al. [36] modelling risk knowledge into an ontology-based semantic network to produce a risk map from which interdependencies between risks can be inferred semantically. Similarly, Wang and Boukamp [49] proposed a corresponding representation and reasoning framework, and Xing et al. [50] developed a domain ontology (SRI-Onto) to retrieve safety risk knowledge in a metro construction project. Their developed ontologies consist of seven main classes namely, project, construction activity, risk factor, risk, risk grade, risk consequence, and risk prevention measure. However, many of these safety ontologies need further validation through case studies and performance evaluation.

Additionally, most of the developed ontologies related to safety management concentrate on the construction phase and only focuses on one or two aspects that eventuate the hazard, such as building element [36] and activity [50]. Little attention has been paid to other aspects such as location and scope of work. The ontology presented here is based on actual incidents extracted from the HSE archive, and considers all the various aspects which can trigger the eventuation of risks. Accordingly, cross-domain information between the H&S silo datasets and the BIM environment (mainly IfcOWL) can significantly improve the design for safety process. It could provide an accessible knowledge base in a structured way where interoperability between different platforms and the golden thread of information can be achieved. This knowledge base also provides an environment for machine learning and predictive analytics.

2.3. *Software applications*

Software applications, the third component of a PtD system (Fig. 1), enable designers to use data for better health and safety work proactively. For hazard visualization, several studies have explored BIM capabilities, addressing high-risk tasks [30], temporary structures [51], safety programs [52], safety and productivity of labour operations [5] and Job Hazard Areas (JHA) [48]. BIM and other technologies such as serious gaming, mobile computing, augmented reality, and virtual reality have been adapted to provide environments for safety training for undergraduate students [53], designers and planners [54] and workers [55]. Indeed, the learning potential provided by visual BIM-based safety tools was a motivational factor for developing the risk suggestion tool reported in this paper.

Rule checking is an area whereby design models can be evaluated against health and safety rules and regulations. When done manually, the work is time-consuming, expensive and error-prone [56]. Therefore, several researchers have developed automatic rule checking to evaluate designs based on configured building regulations. For instance, Zhang et al. [57], Melzner et al. [58], and Zhang et al. [59] proposed a tool to automatically check BIM models against the fall from open/edge risk during the design phase. Other scholars have developed Revit Plugin's against safety regulations [7], for the checking of specific scenarios such as scaffolding construction [51], building elements' characteristics such as depth, height and clash detections [52], temporary structures [60], and user-specified library [8] and construction site layout planning [61]. Automatic rule checking is an important stream of reearch work in the field.

2.4. Expert systems/artificial intelligence (AI)

A further area of application is the development of expert systems: systems that aim to utilize knowledge retrieved from knowledge accumulation and management work through use of artificial intelligence (AI) and "what if" scenarios to provide suggestions related to health and safety. Systems developed to date purport to highlight issues related to design parameters for waste remediation [62], traceability of design data [63], method statements [40], vegetated roofs [64], and site layout planning [65]. More recently, work has brought together the expert system and knowledge based system concept into an overall system architecture: Yuan et al. [7] presenting a complete prototype knowledge base system for detection of safety risks that combines a Prevention through Design (PtD) knowledge base, connected to a BIM environment via a Plug-In. The Plug-In sends feedback to designers through pop-up alert windows containing construction risk identification numbers (IDs) and corresponding pre-control measure IDs in a Revit model. The Plug-In functions through an automated rule-based algorithm that extracts rules from guidance/regulations, using data from the Revit model. Tested on a case study project and verified by professional practitioners as effective and efficient, Yuan et al.'s [7] study makes an important contribution by integrating BIM, a PtD database, a Plug-In and a case study project with designers.

Other expert systems work aims to reduce people's subjectivity in hazard identification by using AI to facilitate hazard identification. For example, data mining has been utilized to automatically identify attributes related to safety from injury reports [37,66], to define the higher likelihood of construction safety hazards taking place [67] and to develop a safety prediction model based on an optimized neural network algorithm [68]. Other researchers have adopted statistical analysis to categorize incidents available in databases such as risk types occurring in case studies spanning 10 years [69], causes of incidents via investigation reports of 571 construction accidents in China [37] and causation factors that eventuated in near misses [35], whilst work has also been conducted into extraction of information manually from regulations and best practices [7].

The above review highlights the evolving nature of digital ICT solutions for the industry and the continuing need for designers to access reliable health and safety data to inform their work. While it is evident that some PtD tools have embraced both explicit and tacit knowledge [8,36,37] others facilitate hazard identification and also offer risk mitigation suggestions. However, there is a lack of tools that holistically integrate explicit and tacit health and safety knowledge with both hazard identification and risk treatment in a BIM environment. Additionally, the ontological concepts used for structuring the data are often not closely related to existing datasetsof health and safety data and knowledge, such as provided by the HSE. This gap is addressed by the BIM Safety Risk Library tool developed by this research. The next section presents the methodology applied in this research.

3. Research methodology

The BIM Safety Risk Library for Construction aims to assist design and construction professionals to better manage their health and safety objectives via proactive use of digital technologies and mobilization of information resources through a PtD approach [7]. Opportunities provided by technologies such as BIM motivated the research team to explore how BIM can be applied to health and safety [8,36]. Comprehensive and continuous industry engagement was recognised as essential from the start: phase 1 of the research (January 2019 – June 2020) aimed to design and deliver a prototype proof of concept tool for both BIM and non-BIM environments.

3.1. Overall approach

The research was divided by work packages; Table 1 details activities in each work package.

This paper primarily reports on work done related to prototype tool design and development (work packages 6–12 in Table 1); earlier work packages are not described in detail here. However, these earlier activities were instrumental in informing the overall research approach adopted.

3.2. Data extraction and loading

The overall data extraction and loading process are presented in Fig. 3. As illustrated, an Extract Transform and Load (ETL) process enabled data from specific sources to be accessible and useable in convenient formats. An ETL process requires a systematic process, which, according to Trujillo et al. [73] consists of six tasks: (1) Selection of data sources for extraction, embracing both explicit and tacit knowledge sources; (2) Joining of data from resources, possibly using focus groups, with the definition of how to merge data sources; (3) Data transforming, including filtering data, calculating derived values, transforming data formats (e.g. use of CSV file); (4) Selection of a target output through which data will be loaded; (5) Attributes mapping: definition of correspondence between source data attributes and attributes of the target; (6) Data loading: the modality of how the target is

Table 1
Project work packages.

Work package	Description
1. Literature Review.	Review of academic literature related to BIM, design and health and safety.
2. Industry Application Review.	Review of current UK industry applications for BIM and better safety management. Identification and examination of two specific applications as potential pilot project platforms.
3. Research Centres Review.	Research centres active in the field identified for possible future collaboration.
4. BIM 4 Health and Safety Group (BIM4H&S).	Establish a working link with the HSE BIM for health and safety industry group.
5. Industry Steering Committee.	Establish an industry Steering Committee to assist with research project direction and overall progress.
6. Risk/Treatment Concept Ontology Development.	Develop appropriate ontology of concepts for construction risk situations and treatment.
7. Risk scenario identification and extraction from HSE data sources.	Identify risk scenarios from the HSE archive resources available. Extract the identified concepts using the ontology (165 RIDDORs; 31 Press Releases reviewed).
8. Designer workshops for treatment response collation.	Via workshops, capture industry expert tacit knowledge (from the industry Steering Committee) to identify treatment actions for the nine scenarios identified covering fall from open/edge risk and concrete in situ primary structures. Treatments (i.e. explicit knowledge) also drawn from relevant industry sources – CIRIA C755 [70]; Design for Construction Safety [71]; CDM 2015 [19]; relevant HSE standards [72].
9. Develop a CSV file from the data collected.	Develop a CSV file of different scenarios and associated treatment actions from the work done.
10. Prototype development.	In collaboration with a BIM software provider, agree interface/facility (e.g. Plug-In) for CSV file deployment and use.
11. Prototype deployment.	Deploy the prototype for industry use.
12. Evaluate the prototype.	Evaluate performance/use of the new prototype to improve functionality and use by designers.

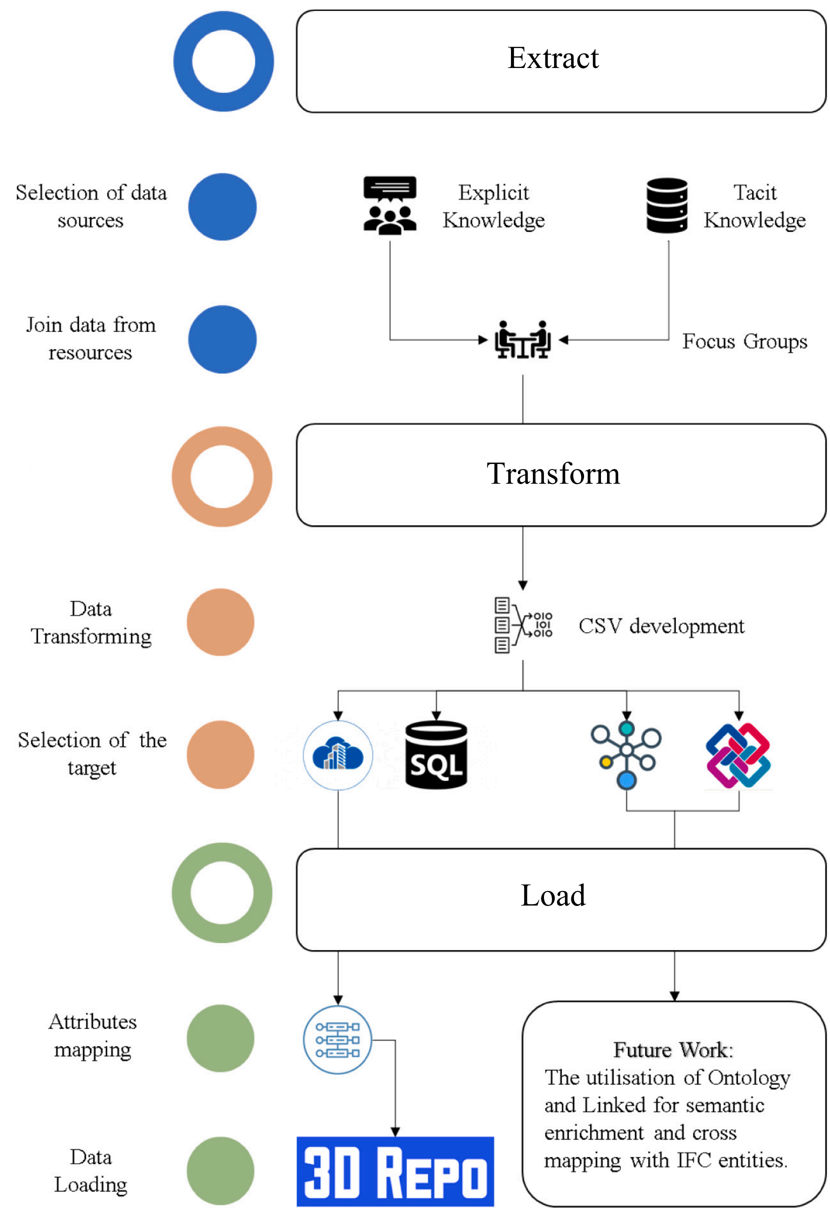

Fig. 3. Extract Transform Load (ETL) process.

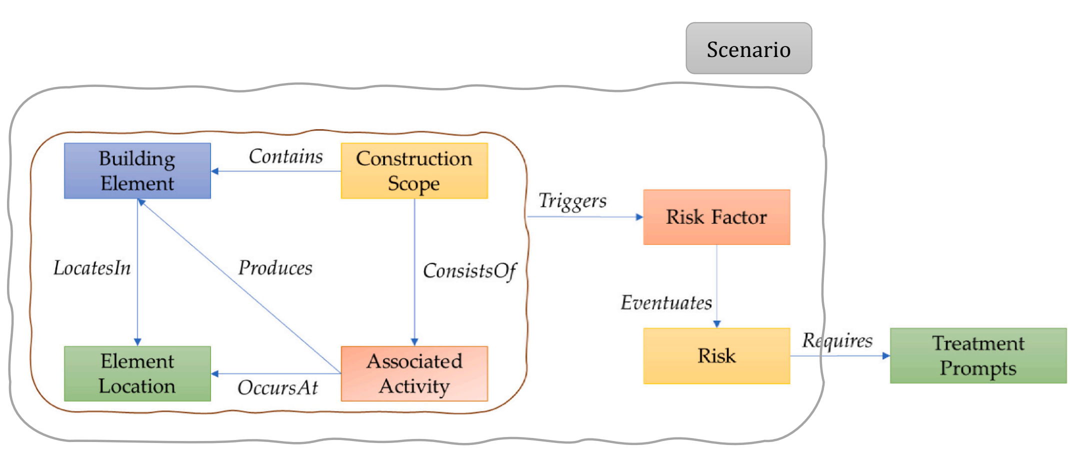

Fig. 4. Risk/treatment concepts and relationships.

populated with the transformed data is defined. The ETL approach was integral to the research outputs described in the following sections.

4. Research results

4.1. Risk/treatment ontology

A conceptual risk/treatment ontology relating to construction accidents and their possible treatments was as a central element of the proposed PtD system. The ontology was formulated following a review of the literature relating to risk taxonomies and important industry sources related to health and safety. Close examination of the HSE archive sources related to health and safety accidents and reports (i.e. press releases and Reporting of Injuries, Diseases and Dangerous Occurrences Regulations (RIDDORs) also informed formulation of the ontology. Consisting of 6 inter-related concepts that together constitute a “risk scenario” leading to a treatment prompt concept (Fig. 4), these concepts became the foundational basis of the PtD knowledge base of the tool.

It was important that the risk/treatment concepts were based on existing industry standards, regulations and guidelines to strengthen their validity and increase the potential for interoperability and standardisation. The risk/treatment ontology concepts are rooted in the following ways:

- Construction Scope. Based on CIRIA C755 CDM 2015 [70] guidelines, the construction scope concept is structured on type of construction work, being divided into five main groups: Group A (general planning), Group B (excavation and foundations), Group C (primary structure), Group D (building elements and building services), Group E (civil engineering). Each group consists of several construction work sectors, categorising the type of related construction work. In total 40 sectors are identified under the five groupings.
- Risk. Based on PAS 1192–62,018 [20], the risk concept identifies different types of risks that could occur in construction. There are 29 possible risks, some related to health and others to safety.
- Building Element. This concept comprises the different elements associated with the eventuation of hazards; elements being classified by related building design disciplines to enable them to be easily assigned to the responsible designer. There are five main groups: structure, architecture, mechanical, electrical, temporary structures.
- Element Location. Based on a review of 196 incidents in the HSE archive, the location concept identifies the characteristics of the location which can be the reason why a risk arises. For prototype development, two main location groups were identified: high-level location and site logistics. High-level group includes locations that could trigger a hazard at a high level such as: openings, edges and spacing between joists. Site logistics group includes locations that can be critical and hazardous during construction and operation/maintenance such as confined area, excavation, and crane area.
- Associated Activity. This concept sub-divides activities into 16 categories; the breakdown structure being at a higher/generic level because the method of construction are usually not fully known during the design stage. The proposed 16 activity categories cover several work activities, commencing with preliminary site-investigation and through to material disposal or re-use. The classifications were captured during the industry workshops.
- Risk Factor. This concept seeks to identify the reason behind the risk eventuation, the risk factor concept being divided into three main groups: physical, material and task. Physical factor comprises factors related to the physical characteristics of an element such as opening, edge, length, and shape. Material group comprises the type of material which could impact the health and safety of workers such as lead and asbestos. Material group includes the material strengths which could be a reason behind the failure of a structure. Task group covers the job-steps which could eventuate a hazard such as manual handling and lifting. Task group also includes the work scopes which repeatedly are associated with specific hazards such as temporary works and excavation.
- Treatment Prompts. This concept identifies the solution suggested by designers to deal with the existing risk. The rationale behind using the word ‘treatment’ instead of ‘mitigation’ is because the word “treatment” is a more neutral term than mitigation: a mitigation plan may not produce the expected outcomes even if carefully designed and implemented. The suggested treatment prompts were classified based on two different concepts: type of treatment and project cycle stage. Type of treatment were based on the general principles of prevention stipulated in the UK Management of Health and Safety at Work Regulations 1999 [74]. They represent the logical process that designers should follow if dealing with a hazard: eliminate, reduce, control (by subsequent design) and inform. Project cycle stage classification consists of four stages: preliminary design; detail design; preconstruction; and finally, site work, temp works, and change control. Each stage will address different issues as work moves from being general/generic to being more precise as the design is refined. Also, each stage will address the same issue differently as the amount of available information increases and opportunities to change a design become limited.

The concepts described and illustrated in Fig. 4 capture a construction risk scenario requiring appropriate treatments. These concepts were subsequently verified by industry experts in focus group workshops (Fig. 3). They were proactively used to engage with the HSE archive of data resources so that information could be identified, extracted and annotated systematically for subsequent use.

4.2. Risk scenario identification

The risk scenario concepts were utilized to annotate and categorize 165 RIDDOR (Reporting of Injuries, Diseases and Dangerous Occurrences Regulations) reports and 31 press releases incidents from the HSE archive. The research team used excel spreadsheets to annotate the datasets based on the identified concepts; each spreadsheet row included the incident and seven columns (each column represents one of the concepts identified). The sub-concepts of each concept were identified as a drop list to achieve consistency. Based on the annotations, it was noted that 85% of the reviewed incidents related to falling from open/edge in in-situ concrete, and these could be categorised into nine different scenarios. Nine scenarios (shown in Table 2) were identified from a careful examination of the RIDDORs and press releases; these scenarios being presented to industry experts in workshops to find the best optimal treatment prompts for addressing them during construction design work.

4.3. Treatment identification

As noted earlier, a safety knowledge database should ideally combine insights from both formal explicit sources and tacit expert knowledge; the treatments for the nine risk scenarios needing to embrace both kinds of knowledge. Therefore, the research team consulted both revelant widely used PtD industry sources and industry experts via workshops to obtain suitable treatments for each scenarios; treatment actions need to be identified and linked to each scenario for designers to select the most appropriate response. The industry sources used to manually identify treatments (i.e. explicit knowledge) include CIRIA C755 [70]; Prevention through Design online resources [71]; CDM 2015 guidance [19]; and relevant HSE guidance [72]. Engagement with industry experts was important to capture tacit knowledge to provide designers with treatments that were practical. Therefore, several workshops were conducted to determine appropriate treatment actions for the nine identified scenarios.

Table 2
Nine scenarios identified from RIDDORs and press releases.

Scenario	Risk	Element location	Building element	Risk factor	Construction scope	Associated activity
One	Fall Open edge	High level Near opening	Slab	Physical Opening	Insitu concrete	Install construction
Two	Fall Open edge	High level Near edge	Slab	Physical Edge	Insitu concrete	Install construction
Three	Fall Open edge	High level Near edge	Flat roof	Physical Edge	Insitu concrete	Install construction
Four	Fall Open edge	High level Between joists	Frame/ Beam	Physical Spacing	Insitu concrete	Install construction
Five	Fall Open edge	High level Near opening-Stairwell	Stair	Physical Opening	Insitu concrete	Install construction
Six	Fall Open edge	High level Near opening-Shaft	Slab	Physical Opening	Insitu concrete	Install construction
Seven	Fall Open edge	High level Near edge	Cladding	Task Lifting	Insitu concrete	Install construction
Eight	Fall Open edge	High level Near edge	Pitched roof	Physical Edge	Insitu concrete	Install construction
Nine	Fall Open edge	High level Near edge	Temporary structure	Task Temp. structure	Insitu concrete	Install construction

In total, five workshops were held with three consultancy firms and two construction and engineering companies (see: Table 3). In total, 33 experts contributed, providing treatments for the presented risks based on their experiences. Each workshop started by introducing the different scenarios, with participants working in small groups to discuss potential treatment prompts for each scenario. Each workshop lasted about 90 to 120 min, with information being captured manually on worksheets, and then inputted onto Excel sheets for further analysis. The outcomes of the five workshops resulted in a collation of 162 treatment prompts for the nine scenarios. This resource of information became a foundational data source for the Safety Risk library.

Fig. 5 is an example completed scenario with associated treatment prompts in a matrix. Once treatment prompts had been identified for all the scenarios, a CSV (comma separated values) file was created showing all the treatments associated to each scenario in the test set (i.e., the nine scenarios identified from RIDDORs and press releases). The purpose of the CSV file was to enable loading of the created knowledge source (embodied in the CSV) into a BIM environment platform.

The CSV file format had several strengths: it allowed data to be saved in a tabular format, facilitating exporting into spreadsheets or other storage database formats regardless of software being used. As well as providing an opportunity to represent data differently (e.g. via a database, website or BIM platforms), the CSV would also make it easier to import and develop an ontology to be shared and reused in several applications. The ontology work would be important for further tool development, as ontologies define the terms used to describe and represent an area of knowledge (e.g. health and safety in construction), although it has been duly noted that software agents can only commit to an ontology expressed in a formal language, while human beings can commit to definitions expressed in natural language [18]. As many applications actively use ontologies to capture relationships and boost knowledge management, the research team contend that providing a working link with further ontological driven work would be important.

4.4. Prototype development

To proceed further, a suitable BIM software provider was identified and approached with a view to collaboration; a prototyping approach being optimal to test the conceptual design and dataset developed in the research. 3D Repo's digital BIM platform was selected for collaboration, as the safety-oriented risk register module within 3D Repo (SafetiBase) has a data structure based on PAS 1192:62018 [20]: the same data structure used in the risk and treatment ontology (Fig. 4). Following the agreement between all parties (HSE, 3D Repo, SafetiBase), a new version of SafetiBase was developed with a new interface feature to accommodate the CSV file (containing the risk scenarios and treatment prompts) via the TeamSpace area of SafetiBase (a 3D Repo feature to host specific information of designers).

This interface enabled users to select relevant scenarios based on the chosen options rooted in the risk/treatment ontology (Fig. 4). After completing the fields by a user, the tool then suggests associated treatment prompts for selection, the user assigning it to a specific location in a 3D model. The new version of SafetiBase also provides a download link to a blank CSV template, enabling designers to populate their own risk scenarios and associated treatment offline, for subsequent uploading to their own design models. A screenshot of the SafetiBase risk/treatment prompt interface is shown in Fig. 6. A complete demonstration of how the tool works, as well as the work leading up to it (described in this paper) is available at https://vimeo.com/425838398.

4.5. Prototype deployment and validation

The research team then invited a small number of companies to trial the tool over the Spring/Summer of 2020. The SafetiBase (3D Repo) prototype with the risk/treatment feature add-in was also promoted via several webinar events, whilst specific companies actively experimented with the tool within their own design teams. Informal feedback indicated a positive reception to the tool. A more formal piloting of the tool in 2021 engaged six different construction projects at an early design stage of the project lifecycle. As noted on Table 4, a variety of companies participated in the piloting of the tool, generating new risk scenarios and treatments to be added to the safety risk library.

The pilot projects were critical for collection of further data for the safety risk library, with use of the tool changing and challenging existing work practices for designers around health and safety risk identification and treatment. The use of industry focus group workshops ensured expert knowledge was captured regarding treatments: further risk scenarios and treatments being sourced from the 6 industry projects piloting the tool in live construction projects at the early design stage. The use of the tool and library were noted as positive and significant by the pilot project organisations. In a survey of pilot project opinion, 11 out of 15 of respondents agreed that the safety risk library can positively impact design decisions, support selection of appropriate treatments to mitigate health and safety risks, and enable leveraging lessons learnt across previous projects. Amongst the comments captured in interviews with users of the tool were the following:

“The structured approach to input risk data is essential…it just helps improve [information] consistency. And characterising the risks in this structured approach makes you think about what the actual risk is, rather than just writing words that might not accurately capture what

Table 3
Designer workshop participant information.

Type of organisation	Participant role	Years of experience	*DE No.	Subtotals	Total
Design, Engineering, and Architecture consultancy firms	Senior Structural Engineer	10–20 years	1	1	
	Senior Electrical Engineer	10–20 years	1	1	
	Senior Mechanical Engineer	> 20 years	1	1	
	BIM Manager	10–20 years	1	1	
	Director	> 20 years	1	1	5
Construction and engineering	Construction Manager	> 20 years	2	1	
	Construction Lead	> 20 years	2	1	3
	Head of Safety Health Environment operations	> 20 years	2	1	
Design, Engineering, and Architecture consultancy firms	Senior Structural Engineer	10–20 years	3	1	
	Senior Electrical Engineer	> 20 years	3	1	
	BIM Manager	10–20 years	3	1	
	Structural Engineer	1–5 years	3	1	
	Mechanical Engineer	1–5 years	3	1	
	BIM Manager	5–10 years	3	1	
	Director	> 20 years	3	2	8
Design, Engineering, and Architecture consultancy firms	Digital Information Manager	10–20 years	4	1	
	Director	> 20 years	4	1	3
	BIM Manager	10–20 years	4	1	
Design, Engineering, and Architecture consultancy firms	Associate Director	> 20 years	5	1	
	Project team manager	10–20 years	5	1	
	Director	10–20 years	5	1	
	CEO	> 20 years	5	1	
Consultant	Commercial Lead	10–20 years	5	1	
	4D Project Lead	10–20 years	5	1	14
	Technical Head	10–20 years	5	1	
Construction and engineering	Design assurance engineer	10–20 years	5	1	
	Managing Director	> 20 years	5	1	
Government agency	Health and Safety Inspector	> 20 years	5	2	
Consultant	Director – Owner	> 20 years	5	1	
Total Number of Participants across the designers' engagement* (DE*) meetings					33

the risk is",

"With the risk library tool you can see the problem…I wouldn't say it has influenced our process, but there is space to make it easier".

A case study showcasing the use of the tool by one of the pilot project organisations provides further insights and is publicly available online [75].

Expert validation came from engagement with industry professionals in relevant groups (e.g. BIM4 Health and Safety industry group) and at industry conference events such as Digital Construction Week 2019 and BIM 4 Water 2019 meeting. Further validation of the BIM-based safety risk library came with winning the Professional Research category award at the 2020 buildingSMART conference: https://www.buildingsmart.org/bsi-awards-2020/winners/ and health and safety software of the year Construction Computing Awards 2021: https://constructioncomputingawards.co.uk.

5. Discussion and contribution

The paper reported on development and use of a new PtD tool to assist designers with their construction health and safety work duties. The creation of a digital tool and risk treatment knowledge base (in the form of CSV file) for a single risk (i.e. falling from an open edge) is based on six inter-related ontological concepts that together constitute a "risk scenario" leading to a treatment prompt (Fig. 4) is a contribution to the improvement of health and safety practice in construction. The risk scenario and treatment ontology is structured on industry standards and datasets within the archive of the HSE regulator and lays the foundation for further potential utilisation for multiple risk/treatment scenarios: the CSV file format assisting with possible future manipulation and use. Furthermore, the risk treatments knowledge base may be integrated into various BIM software platforms or used as a stand-alone information resource on smaller projects. For the prototype, the knowledge base was integrated into an existing BIM software (i.e. SafetiBase by 3DRepo) to demonstrate the utility of the knowledge base in assisting designers to identify appropriate risk treatments by formulating a structured query around aspects of their design.

The interactive tool and BIM Safety Risk library build upon industry standards and guidance (i.e. CDM 2015; PAS 1192:6), extending the stated principles to the digital environment. The ontological representation of health and safety risk scenarios has the potential to be extended to other datasets from industry, opening up the possibility for the linking of data from multiple applications to a shared knowledge base. Additionally, the digital tool facilitates the practical implementation of a PtD and SiD approach through developing an accessible knowledge-based system in a BIM environment. Traditionally, PtD relies on tacit knowledge combined with companies' policies and 2D drawings [27], while other forms of knowledge are not fully utilized, such as domain knowledge from regulations and guidelines, and explicit knowledge from government databases [76]. In fact, this lack of consolidated knowledge has been recognised as one of the challenges that BIM-based knowledge extraction and discovery faces [77]. The BIM Safety Risk library addresses such a need in a practical and utilitarian way.

6. Further work

Further work is now underway to build upon the positive initial reception to the prototype tool. This includes the following:

- Expansion of risk types to include other prominent risks via industry pilot projects. A small number of pilot projects with industry will enable the prototype to be fully tested and critiqued by expert designers engaged in construction project work.
- Further use and mobilization of the HSE archive of accidents/incidents records and other health and safety information to the knowledge base of risk scenarios. Automatically extracting knowledge from these sources using natural language processing (NLP) to expand the knowledge base will be the focus of future work.
- Further evaluation and expansion of the developed ontology in real cases to align with other developed ontologies in the AEC (architecture, engineering, construction) domain. For example, each concept in the ontology could be cross-mapped with Industry Foundation Classes (IFC) schemas such as IfcOwl. Future possible work also includes enhancement of the developed ontology and evaluation in real case studies.

Scenario		Risk	Construction Scope
Scenario 1: Floor with openings (150 < x < 3000)		Fall: From open edge	In situ concrete

Building Element	Element Location	Associated Activity	Risk Factor
Slab	High-Level: Near Opening	Install construction	Physical: Opening

	Eliminate	Reduce	Control by subsequent design	Inform
Preliminary Design	Replace all openings required in floor slabs with precast service openings.	Cast in mesh in openings to reduce risk of person falling through.	Group small floor openings together to create one large opening.	Engage Strucutral Engineer with Architects to assist in design of handrail and guard elements.
	Avoid holes - consider alternatives to achieve design purposes.	Reduce hole sizes.	Locate floor openings away from passageways, work areas, & structure perimeter.	Engage with contractors and temp. works at appointment.
Detail Design	Avoid low walls in circulation areas.	Avoid trap hazards near openings.	Design permanent grating in opening to be installed when opening is created during construction.	Identify covering strong enough to support any loads likely to be placed on it - fix in position to prevent accidental dislodgment.
	Avoid hidden alcoves and offsets.		Specify guardrail systems around floor openings except at the entrance to stairways.	
Pre construction	Avoid risk of objects falling from holes/openings on workers below.	Provide requisite guardrails and toe boards at all slab openings.	Provide warning markings and/or colour change.	Inform contractor to design-in permanent cast-in sockets around floor openings to enable early installation of railings.
			Provide protective grate to support weight of person over opening.	Identify safe working load (SWL) of temporary covers in slab floor and specify fixings.
			Use safety nests fixed directly below the opening.	
Site work, Temp works, Change control	Securely fix cover with adequate safe working load (SWL) over opening with fixings requiring tool.	Ensure work is carried out only when weather conditions do not jeopardise the health and safety of workers.	Provide safe lighting levels, including access and depression.	Inform Site team of any activities when covers or guardrails need to be removed.
	Impact protective measures regularly.		Consider indicating pathways and adding tie-offs.	Site team required to highlight and report any changes on iste affecting the design.
			Every temporary floor opening shall be constantly attended by someone.	Contractor should identify all remaining opening/edges and check the selected permanent safety measures.

Fig. 5. Risk scenario and associated treatment prompt matrix.

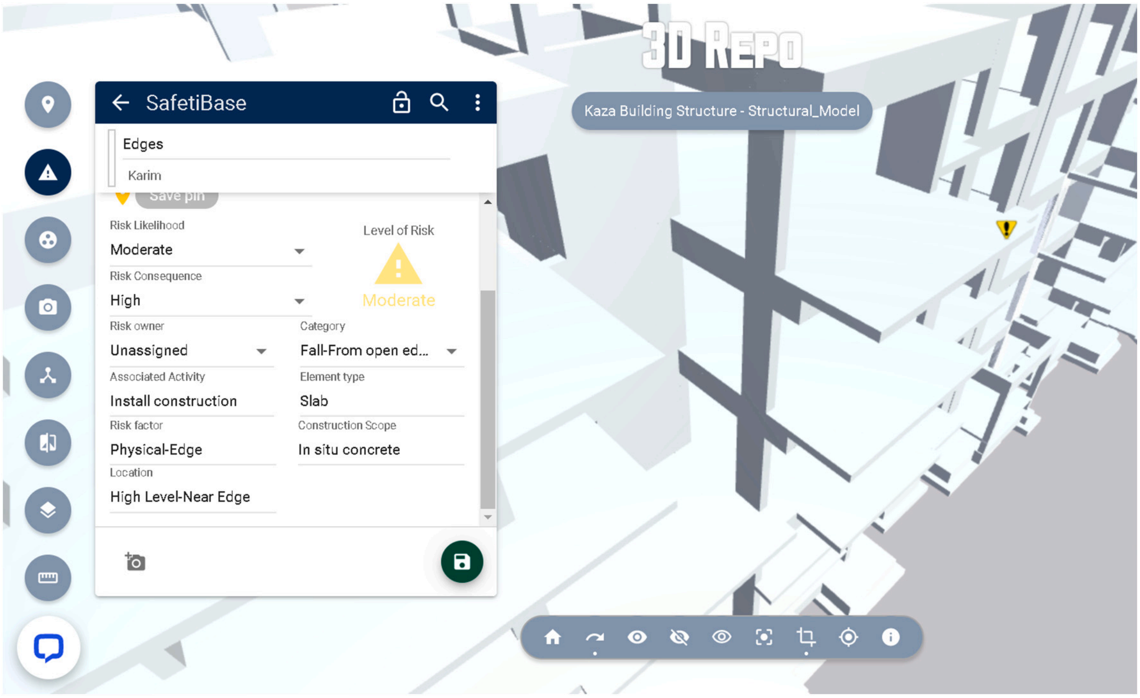

Fig. 6. SafetiBase screenshot with risk/treatment tool add-in.

Table 4
Participating pilot projects.

Pilot project code	Gatekeeper organisation for access to pilot project	Project description	Pilot duration
Alpha	Client	Pharmaceutical cold storage	5 months
Beta	Client	18-storey office block	6 months
Gamma	Consultancy	Specialist facilities for business	3 months
Delta	Consultancy	2-storey shop and 16-storey student accommodation	3 months
Epsilon	Consultancy	Groceries retail store	3 months
Zeta	Client	Road tunnel underneath airway	3 months

- Development of a proof of concept for automatic rule-checking in 3D environment with some prominent risks (e.g. "Falling from Open/Edge") to explore how automatic rule-checking Add-Ins can integrate with the knowledge base in a BIM environment using ontologies and linked data.
- Development a proof of concept for 4D modelling to explore how the knowledge base could be utilized in the 4D environment to take into account the impact of design and construction sequencing on health and safety.

7. Conclusion

The BIM Safety Risk Library is at the forefront of construction PtD research regarding provision of a digital solution for improving construction health and safety. The work makes an important unique contribution to construction safety research and practice by providing planners and designers with ready access to a comprehensive library of knowledge that combines insights from the HSE archive (i.e. explicit knowledge) together with industry expert knowledge (tacit knowledge) to better plan projects with health and safety in mind right from the early stages. This aligns with requirements under both UK Construction Design and Management 2015 regulations (CDM 2015) [19] and PAS 1192:6 [20]. Whilst the conceptual framework has been incorporated into a commercial digital tool (SafetiBase in 3D Repo) that is being actively employed by the industry on BIM-enabled projects, the creation of a foundational library of health and safety knowledge that is accessible and open to further enhancement is a further contribution of the research. In design, concept and application, the construction safety risk library addresses the issues identified in the academic literature as requiring attention and practical solutions: these include the improvement of designer knowledge of risk issues, early identification of health and safety risks in the construction project lifecycle, production of an adaptable and useful learning tool for practitioners and provision of a digital solution grounded in industry standards/guidelines that structures health and safety data into a useable format. The industry piloting of safety risk library on multiple construction projects has demonstrated the utility of the tool in promoting and enhancing implementation of prevention through design (PtD). These contributions and the positive feedback received from pilot projects and industry, reflected through the winning of two awards (buildingSMART 2020; Construction Computing Awards 2021) evidences the contribution of this research to the advancement of health and safety in construction.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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