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Deploying a Building Information Modelling (BIM)-Based Construction Safety Risk Library for Industry: Lessons Learned and Future Directions

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Abstract: A continuing need to improve health, safety and wellbeing in construction has led to multiple research projects and technological innovations. One such innovation is the Safety Risk Library: a repository of data that functions in BIM environments to assist designers and contractors in identifying health and safety risk scenarios and offer suitable validated treatments to mitigate their effects. This paper reports on the deployment of this library in several construction projects across the United Kingdom and reviews expert and practitioner opinions of such digital solutions for improving health and safety in the future. This paper makes several contributions. The description of an effective process for knowledge base creation, including the data extraction workflow, the anonymization of data and the definition of communication channels aligned to project working practices, is instructive for innovation developers, providing informative guidance through lessons learned. The discussion of expert and practitioner opinions of the functional knowledge base to improve health and safety performance could inform further technological developments in the field and provide empirical insights for developers. Additionally, the alignment of the Safety Risk Library to existing industry standards (PAS1192:6) for better sharing and use of structured health and safety information illustrates how digital solutions can connect directly with industry standards to facilitate improvements to working practices whilst also changing perceptions of how risks may be visualised, understood and actioned by duty holders engaged in construction projects.

Keywords: knowledge base library; health and safety; building information modelling (BIM); data management; prevention through design (PtD)

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1. Introduction

The construction industry remains one of the most hazardous industries in the world. It is believed that most accidents in construction can be prevented if addressed during the design phase of projects [1], and under this premise, the concept of prevention through design (PtD) has gained popularity and traction, with designers playing an important role in the identification of potential risks occurring during the construction, operation, maintenance, or disposal of facilities. Interest in PtD has increased as building information modelling (BIM) technologies have matured, with BIM being increasingly adopted by designers and other construction professionals in the United Kingdom (UK) and around the world [2]. However, BIM's integration and alignment with the PtD approach is still very limited.

Previous studies suggested that combining a construction safety knowledge base with a BIM model could contribute to implementing the PtD concept in a number of ways. For example, ref. [3] integrated an object-oriented safety rules database with a BIM model for automated rule checking. Ref. [4] integrated a rule-based knowledge library with a BIM platform to help designers review their models against safety risks. The knowledge base followed a six-level taxonomy to capture safety knowledge, comprising design topics, design elements, work activity, constraints, safety risk and PtD as required design features. Similarly, ref. [5] combined a PtD knowledge base based on regulations, documents and best practices and a BIM platform to check safety risks in a model. This knowledge base consisted of relationships between safety risks and pre-control measures. These research efforts have demonstrated the feasibility and utility of leveraging safety knowledge bases within the BIM process through illustrative case studies. However, the implementation and assessment of this type of approach in real life and operational live construction project settings are largely missing from the literature. Moreover, practitioner reflections on the long-term viability of BIM-based knowledge bases to make a positive difference to construction health and safety work are also lacking. These omissions from the body of knowledge need to be addressed.

The motivating research question of this paper is as follows: do BIM digital solutions have a long-term future for improving construction project health and safety? The objectives resulting from this question are to (a) provide expert and practitioner opinions on a functional and operational digital BIM solution for improving construction health and safety; (b) provide insights from an operational BIM solution to inform further technological developments and provide valuable empirical evidence for technology developers; (c) provide a description of an effective process for knowledge base creation, including data extraction workflow, the anonymization of data and the definition of communication channels aligned to project working practices. This combination of evidence is instructive for innovation developers and the long-term viability of digital BIM solutions regarding how construction health and safety may be improved.

With the above considerations in mind, the Construction Safety Risk Library project commenced in 2019 under the Discovering Safety programme [6]. The project aims to assist design and construction professionals in better managing their health and safety work via the proactive use of digital technologies and the mobilization of information resources via a prevention through design (PtD) approach. Based on a systematic review of digital technologies for enhancing PtD carried out in the earlier stages of this research, ref. [7] suggested that a knowledge base system integrating both explicit and tacit knowledge should be at the core of PtD technological applications. Subsequently, the Safety Risk Library, a knowledge base that maps construction risk scenarios to treatment prompts to assist designers in implementing PtD, was developed. This repository of data draws upon expert knowledge, construction project scenarios and the archive of the UK regulator for health and safety at work—the Health and Safety Executive (HSE). Recognizing that risks may be identified in the design phase of projects [8,9], this work aligns with relevant industry standard guidance, such as PAS 1192-6: 2018 [10], advocating for the better identification, use and sharing of data for improving health and safety in construction. These contextual factors motivated our research team to explore how BIM can be applied to health and safety in construction [4,11] through more proactive structuring and sharing of data at a national level, not just at a project or organizational level.

The Safety Risk Library follows an ontology that characterises a risk scenario based on six data points: construction scope, building element, location relative to the risk, associated activity, risk category and risk factor [12]. Based on this ontology and the associated methodology, a novel tool on an existing BIM platform [13] that hosts the Safety Risk Library was developed [14]. A key feature of this novel tool, the Treatment Suggestion feature, allows users to leverage knowledge from the Safety Risk Library by displaying suggested treatments related to risk scenarios after their identification and characterisation during design. The utility of this tool in a 4D BIM environment has been demonstrated in an illustrative case study [15]. However, the Safety Risk Library requires evidential support from practising engineers, as advocated by [16]. Therefore, this paper focuses on providing such validation by implementing the system in several construction projects and assessing its effectiveness through surveys of practitioners and the gathering of expert opinions. Additionally, this paper provides information and reflections on the information management processes followed for knowledge base creation, including data extraction interventions and the integration of the knowledge base with existing project workflows. These descriptions of an effective methodology and industry engagement strategy are informative for innovators and academics active in this field.

This paper is organised as follows. An initial literature review provides context and background for the paper, reviewing knowledge base libraries for construction health and safety. The Research Methodology Section details the surveying and data gathering processes followed to assess the Safety Risk Library and the work done in its development and creation. The Results Section reviews the data collected, leading to a more detailed discussion concerning digital BIM applications for improving prevention through design (PtD) approaches for health and safety in construction. The Limitations and Future Work Section leads to the final Conclusions section, which draws the insights of the paper together.

2. Literature Review and Context

The construction industry is notorious for poor occupational safety and health performance. For instance, the International Labour Organisation (ILO) [17] estimates that over 100,000 workers die annually in the construction sector. While several factors contribute to the occurrence of such tragedies in construction, studies have noted that design is one of the prominent contributing factors to construction accidents and injuries [18,19]. This link between design and poor occupational safety outcomes has led to the concept of prevention through design (PtD), which is also known as "design for safety" and "safety in design" [20]. PtD involves designers anticipating and "designing out" health and safety risks (through elimination or reduction via design decisions/considerations) associated with a building, civil engineering or engineering construction structure [21]. Whilst several academic studies have highlighted the importance of construction hazard prevention through design [22,23], with some studies reviewing BIM and its application to safety during design work [24,25], a recent systematic review [7] revealed that the implementation of technologies such as BIM for improving PtD has been limited, with a consequent lack of studies into the processes underlying the creation/operation of a functional BIM-based PtD system. Certainly, whilst BIM is a driving force for change in the construction industry [26], with health and safety being a primary research area [4,11], there remains significant space for the improvement of safety through a PtD approach. In a review of twelve studies into designers' use of BIM tools for health and safety work, ref. [22] highlighted that only six tools provided safety suggestions, whilst none of the systems facilitated the objective evaluation of safety risk levels of design attributes, elements or potential safety solutions. Making a similar point, ref. [27] argues that PtD systems should provide information, tools and techniques to enhance the PtD competence of designers and planners, whilst [24] notes that PtD implementation is usually inhibited due to designers' lack of knowledge concerning construction safety and the limitation in tools and procedures available on the market. Such gaps persists even though designers need training on safety, and digital design tools could be useful in assisting them to address safety issues [28]. It may also be argued that whilst recent reviews of BIM and construction safety [29–31] have focused more upon construction than design phase work, the full potential of BIM in relation to safety management has yet to be fully explored [32], including how practitioners relate and interact with a BIM-based PtD system. Whilst academic work has highlighted the value of visualising risks in digital environments [33,34], it should be noted that digital safety technologies based on knowledge base systems are not currently among the most advanced PtD applications. Therefore, there is a need for further research and the sharing of knowledge on the implementation processes surrounding BIM-based knowledge base system creation and the relevant issues academics, practitioners and innovation developers should be aware of when working in this area.

2.1. Knowledge Base Libraries for Construction Health and Safety

Whilst technologies continue to evolve for the improvement of worker safety and well-being, such as the workforce sustainability tool of [35] and the decision-making tool of [36], knowledge bases of data can still provide a foundational dataset of information for multiple applications. In construction, knowledge bases of health and safety information can provide the information to enhance the PtD competence of designers, but such libraries need to embrace tacit expert knowledge as well as explicit regulations and guidelines in open, accessible and functional ways that align with working practices [37]. Such libraries may be created and managed by individual companies or by governmental agencies with responsibility for overseeing health and safety (e.g., the Health and Safety Executive in the UK). Research into the development of libraries (or knowledge bases) recognizes the importance of organizing and structuring information related to safety risks into ordered formats facilitating easy access and interrogation [4,11,38]. For example, ref. [4] developed a design for safety (DfS) knowledge library structured into a six-level hierarchical taxonomy to capture safety knowledge; the taxonomy consisting of design topics, design elements, work activity, constraints and safety risks. Other systems and databases have been developed by researchers to identify possible safety hazards and accident precautions [39], environmental/human risk factors [40] and near-miss information [41]. Such ontological approaches offer a way to integrate and map different datasets from different sources, potentially enhancing collaboration between different stakeholders responsible for better construction safety. Ref. [11] notes that an ontology can offer three main benefits in knowledge modelling and management: (1) the improvement of model flexibility and extendibility; (2) the provision of a robust semantic representation; and (3) enhanced knowledge retrieval by improving the retrieval requests from the conceptual level.

Several ontologies for safety information sharing and job hazards have been proposed. For instance, ref. [42] developed an ontology for job hazard analysis for improving construction safety knowledge in BIM environments. Their developed ontology provides a potential link between safety risk knowledge and the BIM elements by mapping the developed ontology classes with the IfcOwl classes (IfcOwl being the approved ontology of BuildingSMART that represents the Industry Foundation Classes (IFC) schema). Other works have been conducted for the same purpose, such as by [11] to link risk knowledge with related building objects in a BIM environment using ontology-based methodology. Ref. [11] modelled risk knowledge into an ontology-based semantic network to produce a risk map from which interdependencies between risks can be inferred semantically. Based on this semantic retrieval mechanism, applicable knowledge is then dynamically linked to specific objects in the BIM environment. Similarly, ref. [43] proposed a corresponding representation and reasoning framework, and [44] developed a domain ontology (SRI-Onto) to retrieve safety risk knowledge in a metro construction project.

A common shortcoming in many of these ontology-related works is a lack of validation for the ontologies through industry case studies and performance evaluations. As a consequence, mature libraries of knowledge often do not develop due to a lack of stakeholder support, industry commitment to collaborate on the research and access to an archive of relevant data from regulatory sources [45]. Therefore, despite excellent work having been performed in this area, and in the wider field of BIM, for example through the development of BIM maturity models [46], significant opportunities remain to improve practices and create better value from existing datasets relating to health and safety in construction.

2.2. The Research/Knowledge Gap

From the above literature review, it may be stated there is a research/knowledge gap regarding both the processes underlying the creation/operation of a functional BIM-based PtD system and reviews regarding practitioner/expert opinions of them in use on live construction projects. The need for further research and the sharing of knowledge on the implementation processes surrounding BIM-based knowledge base systems motivated the creation of this paper.

3. Research Methodology

Figure 1 summarises the methods followed in the assessment of the Safety Risk Library, described in more detail below.

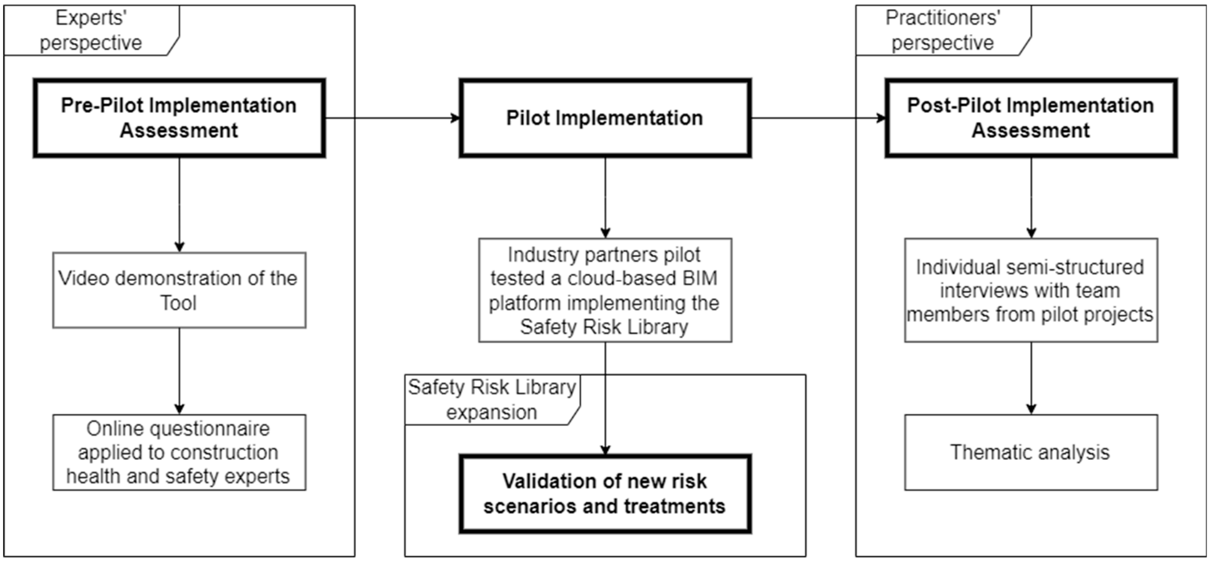

Figure 1. Safety Risk Library methodology, detailing expert and practitioner input.

In this study, a BIM-based tool hosting the Safety Risk Library was pilot-tested on several construction projects across the UK, and its functionality and efficiency were evaluated. This consisted of three distinct activities: pre-pilot implementation/assessment; pilot implementation; post-pilot implementation/assessment.

3.1. Pre-Pilot Implementation Assessment

To ensure the attributes of the developed tool were relevant in the context of construction health and safety management, the opinions of Architecture, Engineering and Construction (AEC) experts in health and safety were obtained through a pre-pilot implementation assessment. Experts viewed a video demonstration of the tool in action and responded to an online questionnaire to provide their opinions. The questionnaire was circulated to a sample of 35 health and safety experts with knowledge of construction health and safety and a minimum of five years of experience in a relevant role [47,48]. These experts were asked to refer others through purposive sampling. From the sample, incomplete and invalid responses were excluded, resulting in 13 valid and complete responses. The demographic of the experts is shown in Table 1. Although 13 respondents is not a large number, the authors believe the detailed responses from the construction health and safety experts provide important and valuable information for the academic and practitioner community. Furthermore, the sample consisted of experts identified according to the guidance in [47], where a minimum of eight experts is recommended, validating the point made above concerning the potential value of small sampling numbers.

The survey was deployed on an online software platform [49]. To rule out invalid responses, the questionnaire started with general demographic questions to gain background information on participants, including areas of expertise and years of experience. Then, participants were shown a video demonstration of the BIM-based tool hosting the Safety Risk Library in use. Subsequently, participants assessed the tool using a five-point Likert scale measuring their level of agreement (where 1 is 'strongly agree', 2 is 'somewhat agree', 3 is 'neither agree nor disagree', 4 is 'somewhat disagree' and 5 is 'strongly agree') on statements about usefulness; the potential to leverage lessons learnt across multiple projects; ease of use; alignment with regulations and guidelines; the potential to affect design decisions and management processes; the potential to enable collaboration; and the potential to improve health and safety in construction; these statements are provided in Table 2. Further feedback was collected through open-ended questions. The positive response from this pre-pilot assessment led to a full pilot implementation.

Table 1. Demographic information of the survey experts.

Expert ID	Area of Work	Experience in the Construction Industry (Years)
EXP-01	Design	45
EXP-02	Other (specify): all stages	41
EXP-03	Other (specify): all stages	40
EXP-04	Design	5
EXP-05	Other (specify): all stages	44
EXP-06	Strategic planning	15
EXP-07	Construction	33
EXP-08	Design	40
EXP-09	Construction	33
EXP-10	Construction	49
EXP-11	Design	33
EXP-12	Other (specify): CDM Principal Designer	35
EXP-13	Design	28

Table 2. Tool evaluation statements.

Item
Supports the selection of appropriate treatments to mitigate H&S risks
Enables leveraging lessons learnt across previous projects
Appears easy to use
Categorising risks is useful
Seems aligned to industry regulations and guidelines (CDM 2015/PAS 1192-6)
Could positively impact design decisions
Enables a more collaborative environment to perform H&S risk assessments
Could improve organisational H&S management processes
Has the potential to improve H&S in construction

3.2. Pilot Implementation

During the pilot implementation phase, the developed tool hosting the Safety Risk Library was implemented by several industry partners as part of their construction safety management processes in live projects during the early design stages. A total of six companies participated, contributing a variety of project types (e.g., pharmaceutical cold storage; airway road tunnels; grocery retail stores). In addition to pilot testing the tool, new risk scenarios and treatments identified by the users during this phase were also incorporated to the knowledge base. Details of the pilot projects are given in Table 3.

Table 3. Pilot project type, value, duration and users.

Project Type	Value Range (Millions)	Client Type	Pilot Duration (Months)	Designation of Team Using the Tool
Industrial	GBP 1–10	Private	1–6	Project team
Infrastructure	Over GBP 100	Private	1–6	Architectural, Structural and Mechanical Design team
Commercial	GBP 1–10	Public	6–12	Principal Designer
Industrial	GBP 10–25	Private	1–6	Principal Designer
Residential	Over GBP 100	Private	1–6	Principal Designer
Commercial	Over GBP 100	Private	6–12	Health and Safety Manager

Figure 2 presents the step-by-step process for the extraction, anonymization and integration of data from the pilot projects into a larger system—the Safety Risk Library. The risk scenarios and treatments inputted by pilot projects were retrieved periodically from the cloud environment, with the data being anonymized through the removal of sensitive or project-specific information. Risk scenarios and treatments were reviewed by the research team in fortnightly 2 h workshop sessions; the retrieved treatments were synthesized and organized within the corresponding treatment matrix, and a tabular form designed to categorise the data points of the risk scenarios and treatments described in [14]. Further treatment prompts were added to each risk scenario using the treatment matrix format based on the experience of the review panel and a review of the grey literature. An average of five risk scenarios were reviewed each session, with the resulting data being added to the Safety Risk Library in a Comma-Separated Value (CSV) format. The enriched version of the knowledge base would then be loaded back into the BIM-based tool so that other pilot projects could leverage and re-use the captured knowledge. The workflow process enabled data to be collected in a non-intrusive way and was an effective methodological approach.

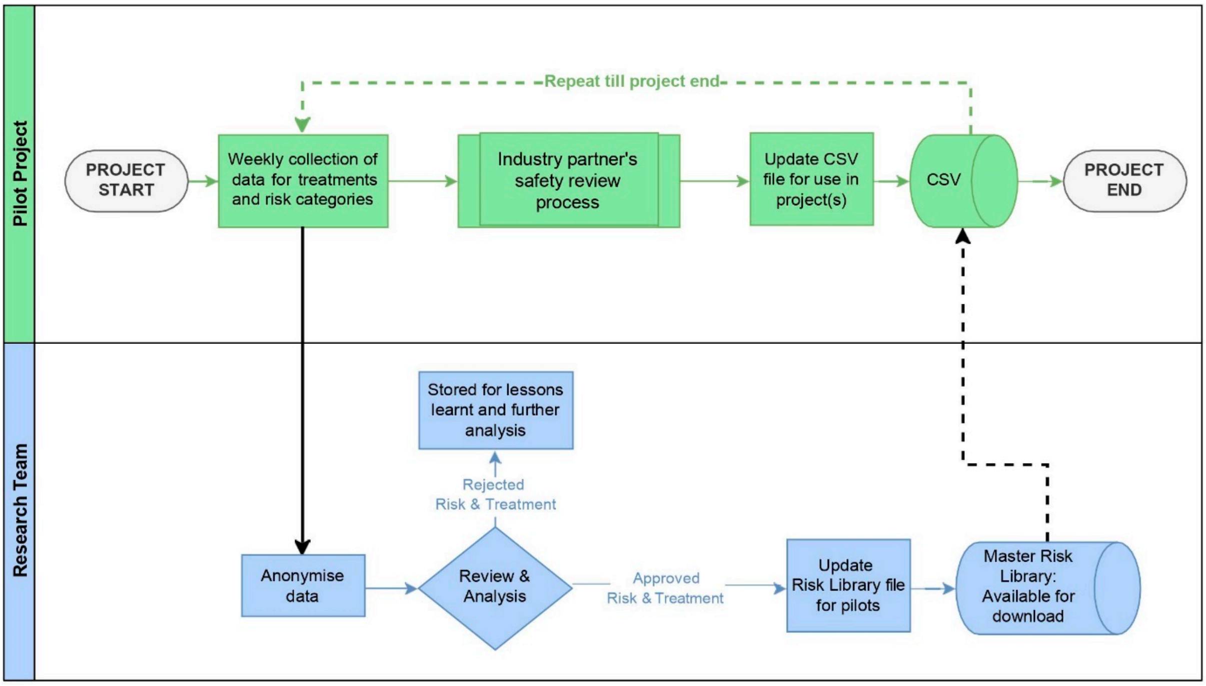

Figure 2. Data workflow for knowledge base creation.

Validation of New Risk Scenarios and Treatments:

Validation activities were carried out that aimed to assure the quality of the data from the pilot projects added to the knowledge base. Two activities were conducted, an industry workshop and fortnightly review meetings. Pilot project participants were invited to participate in an industry-focussed workshop to review three selected risk scenarios and complete their respective treatment matrices. Participants were broken into two separate groups to review the selected scenarios and to provide treatment prompts for them using the treatment matrix format. The responses from both groups were collated by the research team.

As noted, risk scenarios and treatments retrieved from the pilot projects were reviewed by the research team fortnightly in 2 h workshop sessions; the retrieved treatments were synthesized and organized within the corresponding treatment matrix. During these meetings, further treatment prompts were added to each risk scenario based on the experience of the review panel and a review of the grey literature, such as the Construction Design Management (CDM) CIRIA guidance for designers [50]. An average of five risk scenarios were reviewed during each session; the resulting risk scenarios and treatments were appended to the library knowledge base as a CSV file. Risk registers from similar past projects shared from the pilot projects were also reviewed in these sessions to include treatments that had been reported for similar risk scenarios. A caveat to this approach was that the risk registers utilised did not follow a standardised data structure, making the task of mapping treatments to characterised risk scenarios difficult.

3.3. Post-Pilot Assessment

The final stage of piloting the library was to conduct a post-pilot implementation assessment.

Individual semi-structured interviews were conducted with team members from five of the pilot projects directly using the tool. Due to unavailability during the study, an interview with a user from the sixth pilot project could not be conducted. The interviews were video-recorded and transcripts used to find recurring themes through a thematic analysis. The interviews aimed to understand the impact of using the Safety Risk Library, as well as the approach to characterising safety risks, on the safety management processes. Table 4 shows the list of questions asked during the interviews. Table 5 shows the demographic information of the interviewees.

Table 4. Interview questions.

Block of Questions	Question
General questions	1. Before the pilot study, what was the typical process and activities that you and your organisation followed to manage safety risks in your projects? 2. How did your organisation incorporate the tool into its day-to-day activities and process of your pilot project? 3. How did other stakeholders in your project facilitate or hinder the implementation of the tool in your pilot project if at all? 4. How has the implementation of the tool in your pilot project influenced or changed the safety management process in your organisation?
Questions about the use of the tool	1. How has using the tool to categorise risks (using a scenario/treatment ontology) influenced or not influenced the way in which you think about safety risks in your projects? 2. Tell me about your experience using the tool to identify and categorise safety risks 3. Which features of the tool did you find to be very useful? 4. Which features of the tool would you suggest should be improved and what would the improvements be? 5. Are there any other areas of construction health and safety work that may benefit from digitalisation and use of a data structure approach?
Closing question	1. Is there anything else you would like to add before we end?

Table 5. Demographic information of pilot interviewees.

Role	Experience
Construction Safety, Health and Environment Lead	Over 30 years
Health and Safety Manager	10–20 years
Health and Safety Consultant	10–20 years
Information Manager	Over 30 years
Principal Designer	5–10 years

4. Results

4.1. Pre-Pilot Implementation Assessment

The online questionnaire was open for five weeks and received 35 visits. Twenty-two responses were excluded from the analysis because the respondents did not meet the expertise inclusion criteria or because more than 50% of the questions had incomplete responses. Thirteen valid and complete responses from construction health and safety experts were considered for the analysis of the survey. The respondents had 33.9 years of experience on average. Table 6 shows the area of work in which the respondents are typically involved. The majority of the respondents typically perform risk assessment of their projects as part of a team. Figure 3 illustrates the frequency with which respondents typically use different tools to manage safety information, with spreadsheets being the most used.

Table 6. Respondents' area of work.

Area of Work	Responses
Strategic planning	1
Design	5
Construction	3
Operations and maintenance	0
Other (specify)	4
All stages	*3*
CDM Principal Designer	*1*

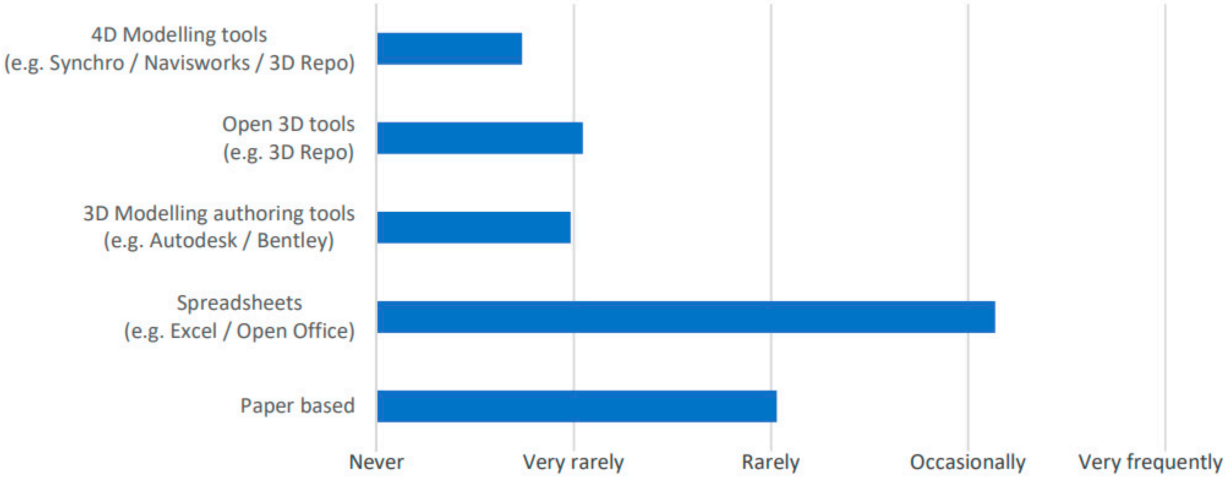

Figure 3. How often respondents use these tools to manage security information.

Figure 4 depicts the level of agreement of the respondents regarding the nine attributes of the tool assessed in the survey. A total of 11 out of 13 participants also responded that they would be interested in using the system and the Safety Risk Library in their projects. The answers to the open-ended question 'What are the potential challenges to adopting this tool?' reveal that the main concerns of respondents related to the licensing costs, the time required to train staff to use the system and the level of skill required to use the system. Two respondents mentioned that the system requires having a 3D model of the project to be useful, which is often not available, especially in the early design stages.

4.2. Pilot Implementation

Knowledge Base Expansion

As a result of piloting the library, the knowledge base was expanded to contain 401 treatment prompts for 31 risk scenarios related to 11 different risk categories. The resulting dataset is described in a separate data article [51], which also signposts the repository that holds the most up-to-date version of the Safety Risk Library.

4.3. Post-Pilot Assessment

The findings from the individual interviews revealed that safety management approaches followed by pilot project organisations before implementing the BIM-based tool hosting the Safety Risk Library involved using spreadsheets to capture risks, mitigation measures, and any residual risks. Such information was typically captured during project workshop sessions where designers and other stakeholders reviewed 2D drawings together. The majority of the interviewees highlighted that the spreadsheets did not follow a consistent data structure approach in terms of how safety risk data are categorised. The approach to implementing the proposed tool was not uniform across all the pilot project organisations. Three interviewees stated that they implemented the tool in parallel with their usual safety management process, whilst two interviewees mentioned that they incorporated the use of the tool into their usual process, using it in project workshop sessions, discussing risks and issues and inputting information into the system instead of using spreadsheets. Another participant implemented the system after their usual approach had taken place. In this particular case, the tool enabled the project team to identify and remove two critical risks that had been previously overlooked. This lack of uniformity in the implementation approach was due to different levels of support from internal and external stakeholders across the selected projects. One interviewee mentioned that external stakeholders in their project were concerned about the potential liability of suggesting safety risk treatments for the wider industry. In another pilot project, the interviewee struggled to obtain engagement from the internal design team and approval to trial the tool from the client. Other interviewees shared that adopting the tool in their projects was equally supported by clients, senior management and the team. These different reactions to using this innovative tool highlight the challenges faced by digital technology innovators.

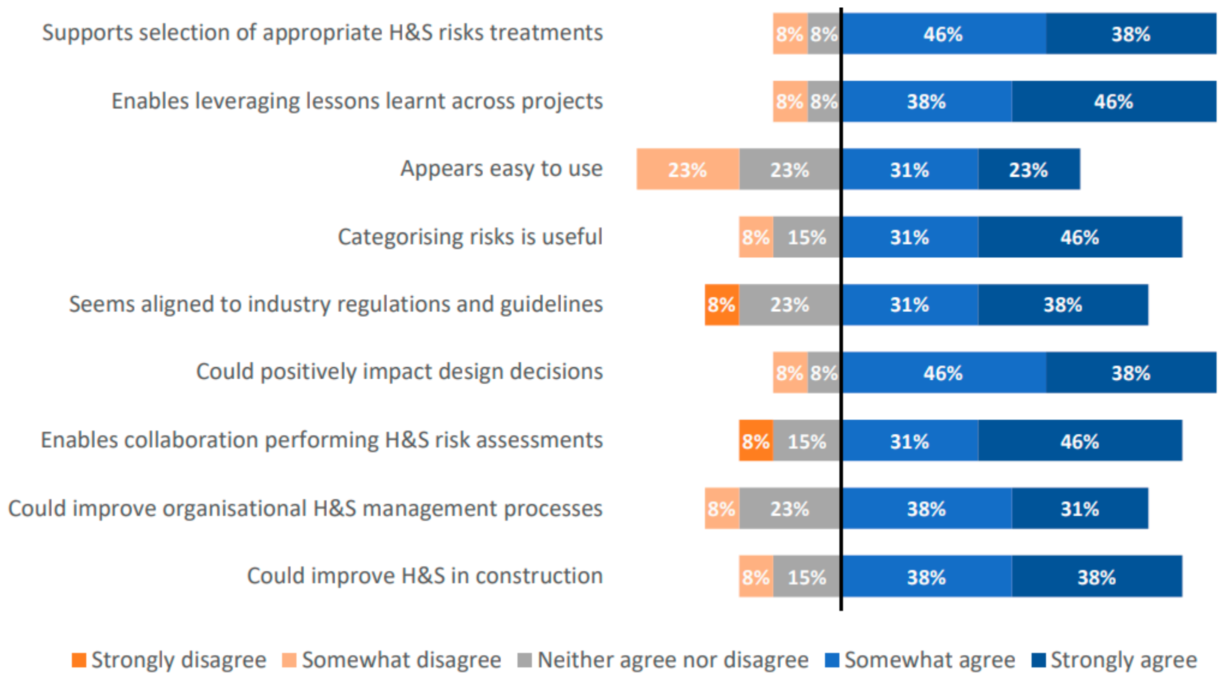

Figure 4. Results of the assessment of the Safety Risk Library.

Interviewees found the risk scenario/treatment ontology valuable in characterising safety risks. However, some found that classifying the identified risk scenarios into the categories provided was a difficult task. Nevertheless, the participants pointed out that familiarity with the concepts resulting from constant use of the tool facilitated the process. Moreover, some participants agreed that characterising the risks in a structured approach encouraged thinking more about the actual implications and meaning of the identified risks. A few of the interviewees also stated that there was a need to capture other risks not related to safety in a similar fashion for overall asset information management. Additionally, the interviewees perceived that adding safety information to a BIM model of their projects and pinpointing where the risks are on the model adds value to their current safety management processes, since it makes it easier to visualise where a problem has been identified, with the majority of participants agreeing that this was one of the main benefits of the tool. The findings of the interviews reveal that this way of visualising safety risk information enables a more collaborative environment to identify further risks and select related treatments.

As noted, when a team of designers reviewed their model using the proposed tool after having gone through their usual risk identification process, they were able to identify and design out two critical risks on their project.

As noted, several pilot project teams used the BIM-based tool hosting the Safety Risk Library in parallel with their usual safety management approaches based on the aim of disrupting their day-to-day activities and usual processes as little as possible. Only one pilot project incorporated the tool into their standard safety management process. Going beyond the scope of the tool piloting phase, this pilot project participant granted tendering parties access to a digital model containing identified safety risks within the tool. This facilitated bidders' awareness and understanding of the risks, leading to more precise tender cost estimates. Specifically, the cost was associated with the construction phase, where previously identified risks were no longer unexpected and could be accurately factored in. This was a further unexpected innovation triggered by the project team using the Safety Risk Library.

5. Discussion

This paper has detailed the work processes associated with implementing a new construction health and safety knowledge base and the tool hosting it for industry. The pilot projects were critical for the collection of further data for the knowledge base, with use of the tool changing and challenging existing work practices for designers around health and safety risk identification and treatment. The evaluation of the tool hosting the Safety Risk Library by industry practitioners validates the premise of leveraging construction safety knowledge across multiple projects and organisations via a BIM-based tool. The feedback of construction safety experts reveals that approximately 85% either somewhat agreed or strongly agreed that a knowledge base can positively impact design decisions, support in the selection of appropriate treatments to mitigate health and safety risks, and enable the leveraging of lessons learnt across previous projects. Amongst the supportive comments captured in interviews with users was the following: "The structured approach to inputting 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 the risk is".

One challenge to tool adoption encountered during the piloting phase was the lack of support from external stakeholders—several initially interested parties withdrew from pilot projects because their clients were reluctant to test a new tool in their projects or change their usual safety management processes. This experience is perhaps characteristic of launching innovations in project-based settings. However, we observed a more positive use of the tool and feedback from pilot projects where both clients and owners acknowledged the importance of PtD. This observation aligns with [52,53], in which the authors found that owner/client organisations that prioritise PtD can promote its implementation. Top management participation and organisational commitment to help meet a client's needs were also two predictors for safety technology adoption outlined by [36]. In contrast, more challenging situations arose where designers were not contractually obliged to participate in piloting the tool by their clients. In these cases, designers expressed both fear of liability for suggesting treatments for common safety risks to other organisations and concerns regarding the direct cost of time spent identifying risks and selecting treatments. Such challenges were also identified by [54,55] as potential barriers preventing designers from contributing to advancing PtD methods on projects.

A benefit of the tool highlighted by pilot users is that adding safety information in a structured way to BIM models makes it easier to visualise where risks are and communicate them to other stakeholders. This finding aligns with prior studies on safety risk visualisation and ontologies, such as [56], in which the authors reported that it has been proven in the literature that virtual 3D site models can improve the understanding of the environment where prevention measures are required before work execution. Equally, ref. [11,44] argues that structured and unified forms of risk information facilitates knowledge sharing among different parties and risk identification.

The tool hosting the Safety Risk Library provides functionality in an operational space that improves the way risk is managed, potentially leading to more dynamic ways of interacting and managing risks than static Excel spreadsheets. Moreover, the ontology and overall approach aligns with industry standards and regulations ([10,50]) that advocate for better sharing of data at a national level (not just project or organizational). Thanks to active collaboration with the HSE, the UK government regulator for workplace health and safety, the library has a dynamic and vital connection with a government body dedicated to improving construction health and safety.

Limitations and Future Work

Some limitations of this research should be reported. Firstly, some users of the knowledge base reported that the foundational ontology did not contain sufficient categories to characterise a risk scenario accurately. Although increased use of the tool and familiarity with the concepts facilitated the process, it is important to acknowledge that this issue can lead to incorrect or inaccurate categorisations. Secondly, the Safety Risk Library needs to scale up usage across the industry, but this is a challenge faced by every knowledge base aiming to be comprehensive. This multi-faceted challenge requires attention on several issues: communication/publicity; senior management support and drive; software issues; more explicit value data generation regarding tool use at the company/project level (metrics); and the tackling of any contractual/organisational challenges with the use of the tool.

6. Conclusions

The motivating research question of this paper of whether BIM digital solutions have a long-term future for improving construction project health and safety has been met through the presentation of expert and practitioner opinions on an operational digital BIM solution (the Safety Risk Library) and the description of an effective process for knowledge base creation, including the data extraction workflow, anonymization of data and definition of communication channels aligned to project working practices. Whilst the research findings are informative and instructive for innovation developers, the opinions of experts and project practitioners reflect on the long-term viability of digital BIM solutions for improving construction health and safety work. The reported research addresses the continuing need for digital solutions to assist designers with their prevention through design (PtD) work. Through the description of the information management processes followed in knowledge base creation (i.e., data extraction process; knowledge base workflow; effective industry engagement process), this paper contributes to the sharing of knowledge on productive and successful industry engagement strategies: a vital aspect for any innovation aiming to be adopted on a bigger scale. The combination of sourcing data from industry construction projects (via pilot projects) and the HSE archive of construction health and safety incidents resulted in a firm foundational knowledge base ready for further development and expansion. The development of a new construction health and safety knowledge base was received positively by industry stakeholders and by the six pilot projects. This paper provides empirical evidence that the concept of a BIM-based tool to assist in construction safety management is valid and beneficial, with the findings demonstrating that visualising safety information within a BIM environment provides context to identified risks, facilitating understanding and communication. Overall, construction safety experts and industry professionals considered that the proposed approach of using BIM models to identify safety risks and finding treatments within a knowledge base could positively impact design decisions and overall construction safety. Moreover, the proposed approach also challenges the current working practice of using spreadsheets to capture and communicate safety risks to other stakeholders. These findings underline the importance of expanding BIM adoption for improving health and safety management in construction, whilst also informing further technological developments in the field.

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