A method to implement prevention through design using 4D BIM

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Abstract
Prevention through design (PtD) highlights the importance of foreseeing safety risks in construction projects and proposing ways to mitigate them. The BIM Risk Library tool is a feature within a cloud-based BIM application designed to implement PtD effectively. This paper reports on the outcome of a series of workshops where a group of designers and construction safety experts used the BIM Risk Library tool and 4D BIM to perform a safety risk assessment collaboratively. The purpose of the workshops was to explore how a 4D model can support the traditional construction safety management processes at early design stages, with a focus on the safety risk identification and treatment selection processes. Results reveal that 4D BIM can effectively support such processes by facilitating visualising a particular point in time in the project, enabling the identification of risks that could have been overlooked and providing a collaborative environment that favours active engagement.

Keywords: Construction safety, BIM, 4D, Prevention through design

1 Introduction
The concept of prevention through design (PtD) has gained popularity in the past decades to address the safety challenges that the construction industry faces. PtD encourages designers to anticipate potential risks occurring during the lifecycle of facilities as early as possible and to propose means to eliminate, reduce, control or inform on such risks. A major constraint to effective implementation of PtD is the lack of appropriate tools and technologies to apply the required knowledge and skills to identify potential risks in design models (Hossain *et al.*, 2018; Jin *et al.*, 2019; Yuan *et al.*, 2019).

The BIM Risk Library tool is a feature within a cloud-based BIM application (3D Repo Ltd, 2020) designed to implement the PtD concept in construction projects. It leverages crowdsourced expert knowledge and safety regulations of the United Kingdom (UK) through a database that maps safety risk scenarios to treatment prompts that can eliminate, reduce, control or inform on the risk at relevant phases of a construction project. A key advantage of the BIM Risk Library tool is that it is rooted on a risk/treatment ontology that encourages designers to characterise risks based on a set of concepts with a robust foundation in industry guidelines and standards.

In this paper, we report on the outcome of a series of workshops where the BIM Risk Library tool was used collaboratively by a group of designers and safety experts to identify risk scenarios and propose treatments in a construction project using a 4D BIM model. Results reveal that 4D BIM models can effectively support the construction safety risk assessment process by facilitating visualising and thinking of a particular point in time in the project, which enables identification of risks that could have otherwise been overlooked. Moreover, using 4D BIM models in safety risk review meetings enables a collaborative environment that promotes active engagement.

2 Background

2.1 Overview of the Risk Library and the BIM Risk Library tool

The Risk Library is a database that maps construction safety risk scenarios to treatment prompts that can eliminate, reduce, control or inform the risk. Risk scenarios are characterised by six data points: (1) construction scope, a concept based on CIRIA C755 CDM 2015 (Ove Arup and Partners and Gilbertson, 2015); (2) building element; (3) location relative to the risk; (4) associated activity; (5) risk category, a concept based on PAS 1192-6 (British Standards Institution, 2018); and (6) risk factor.

An existing cloud-based BIM application (3D Repo Ltd, 2020) developed a feature (commercially available as the new version of 3D Repo's SafetiBase) that adopted the Risk Library and its data structure to enable users to add a layer of safety risk information to BIM models. Furthermore, the BIM Risk Library tool enables users to leverage the knowledge contained in the Risk Library by displaying existing treatment prompts associated to risk scenarios identified by the users.

2.2 4D BIM for construction safety management

Recent studies have concluded that the adoption rate of 4D modelling for construction safety management is low and that, therefore, the industry still doesn't see 4D modelling as standard practice for construction safety management (Swallow and Zulu, 2019). Golizadeh et al. (2018) argue that there is a lack of understanding of how to use 4D BIM efficiently to address accident causations related to risk management, work scheduling and site constraints. Zou et al. (2017) suggested that research in the area of BIM-based safety management should focus on implementation methods and processes and on integrating traditional safety management with new technologies, among other things.

Therefore, the question that arises is how can 4D BIM be utilised to support the traditional safety management processes? In the context of PtD, we are particularly interested in implementing this technology at early design stages of construction projects.

3 Methodology

The main focus of this research was to explore how a 4D model can contribute to the construction safety risk assessment process at early design stages. Additionally, the research also focussed on how 4D modelling can enhance safety risk visualisation. A workshop series was adopted as the research methodology. Workshops are considered an appropriate method to identify, articulate and explore fuzzy problems in research areas involving technology (Ørngreen and Levinsen, 2017). Participants of the workshops were selected by purposive sampling from expert panels formed in previous stages of the research project based on their knowledge and experience in the field of construction safety. Purposive expert sampling was used to select the relevant stakeholders, as this approach is useful in new areas of research where there is lack of observational evidence (Etikan *et al.*, 2016). Workshop participants included experts from industry, government agencies, consultancy firms and academia to incorporate a wide range of different perspectives into the sessions. The participation mode of the workshop was collegiate, as researchers and participants contributed in a mutual process controlled by the participants (Ørngreen and Levinsen, 2017). This participation mode was selected to ensure that the participants had as much control over the research process as the researchers, leading to the development of a shared vision in regards to which scenarios were more valuable to focus on, and allowing that the answers to the research questions emerged from the activity.

During the workshop sessions, participants performed a preliminary safety risk assessment and identified safety risks using a 4D BIM model of a 16-storey residential building. Such a model was developed to include temporary structures, such as shoring and scaffolding, which are often missing from traditional BIM models (Kim et al., 2018) to ensure that adequate project-specific spatiotemporal information was available. The identified risks were captured within a cloud-based BIM application designed to implement the PtD concept in construction projects. Indicative 3D pins were placed in the model to visualise the points in the model where risks where identified. Subsequently, risks were characterised according to the Risk Library ontology, depicted in Figure 1. A treatment to mitigate each risk scenario was proposed. Where appropriate, a start and end time were also provided to the risk to indicate its duration in the context of the 4D model for visualisation purposes.

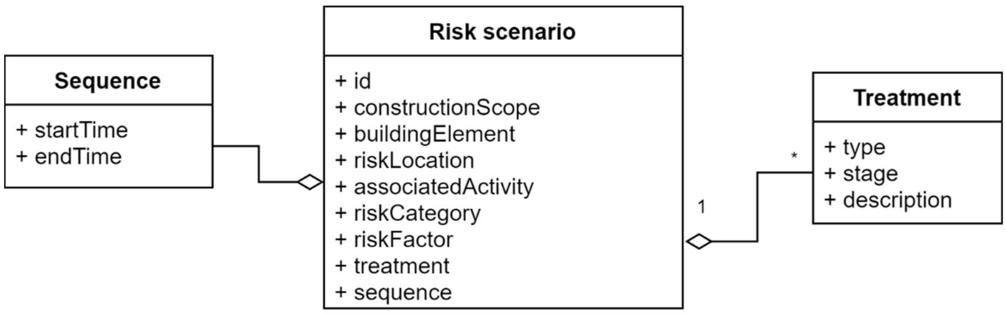


Figure 1. Risk scenario class diagram

Finally, workshop participants engaged in focus group discussions to compare the 4D BIM-supported safety risk assessment process to the traditional safety planning approach that relies on 2D drawings, tacit knowledge and regulations (Choe and Leite, 2017). The focus group discussion segment of the workshop sessions aimed to answer the main research question. Figure 2 outlines the basic structure of the 1.5-hour workshop sessions. As previously noted, participants were in control of the workshop sessions excluding the welcome and focus group discussion segments, in which the researchers adopted a moderator role. Thus, the process in between those segments did not necessarily followed a sequential order.

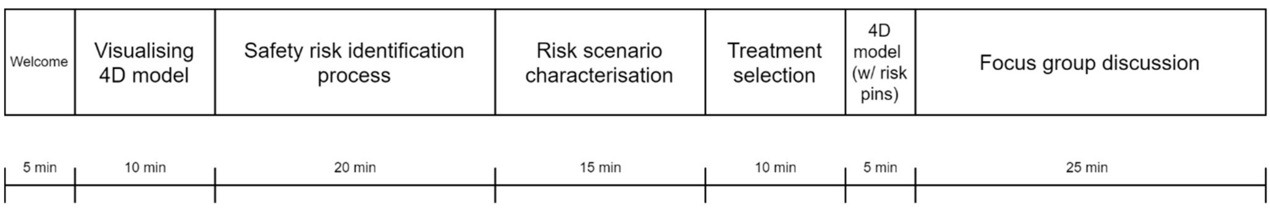


Figure 2. Workshop session basic structure

4 Results

4.1 4D BIM as a supporting tool in the safety risk assessment process

This study was carried out to explore how a 4D model can support the construction safety risk assessment process and enable informed decision-making at early design stages. The majority of the participants agreed that without the BIM model, some of the safety risks identified during the workshop would have been overlooked until later in the project. In particular, visualising the 4D model instead of a static model was considered invaluable to identify risks associated with temporary works. For example, Figure 3 depicts a risk scenario in which personnel working inside an excavation would be at risk of being struck by the temporary props highlighted in yellow if they fell on them. The majority of the participants also agreed that 4D facilitates thinking of a particular point in time in the project, which could result in identifying risks that are not evident from static BIM models representing the finished product.

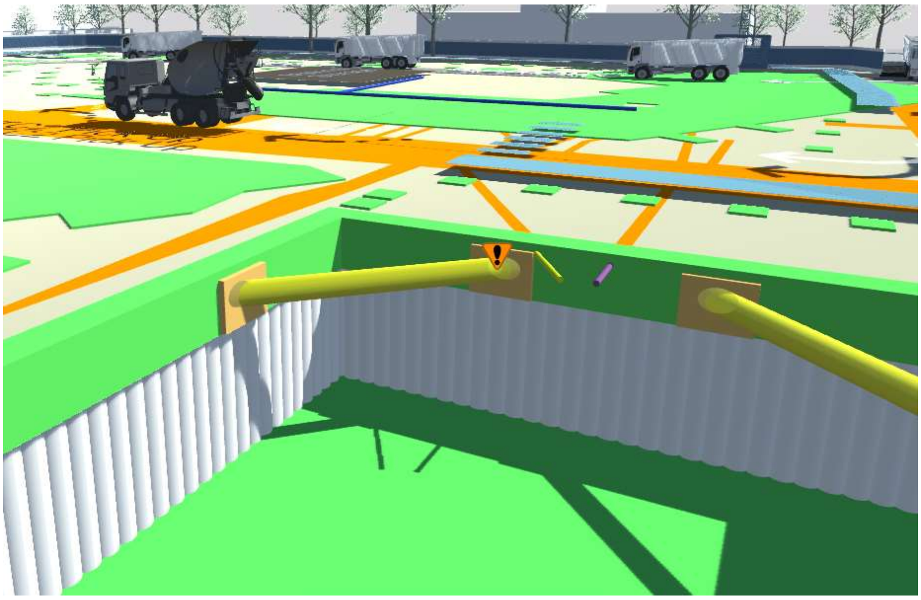


Figure 3. Identified risk scenario associated with temporary works inside an excavation pit

One participant mentioned that by identifying safety risks and marking them on the BIM model, there was potential to generate "a more meaningful" risk register, since the identified risks were project-specific rather than the more general type of risks typically included in risk registers. Another participant added that this approach provides a dynamic risk register in a 4D environment.

Participants also highlighted that the results of the safety risk identification and treatment selection processes were improved when working collaboratively. In regards to this remark, one participant said that working with 4D models promoted active engagement from those involved in the activity. The researchers noticed that all the workshop participants were in fact actively engaged and participating in both the risk identification and treatment selection processes. Another participant emphasised that the combination of visualising the 4D mode with the interactive discussion surrounding selection of treatments for risks prompted thought and reflection, which was very valuable to the process.

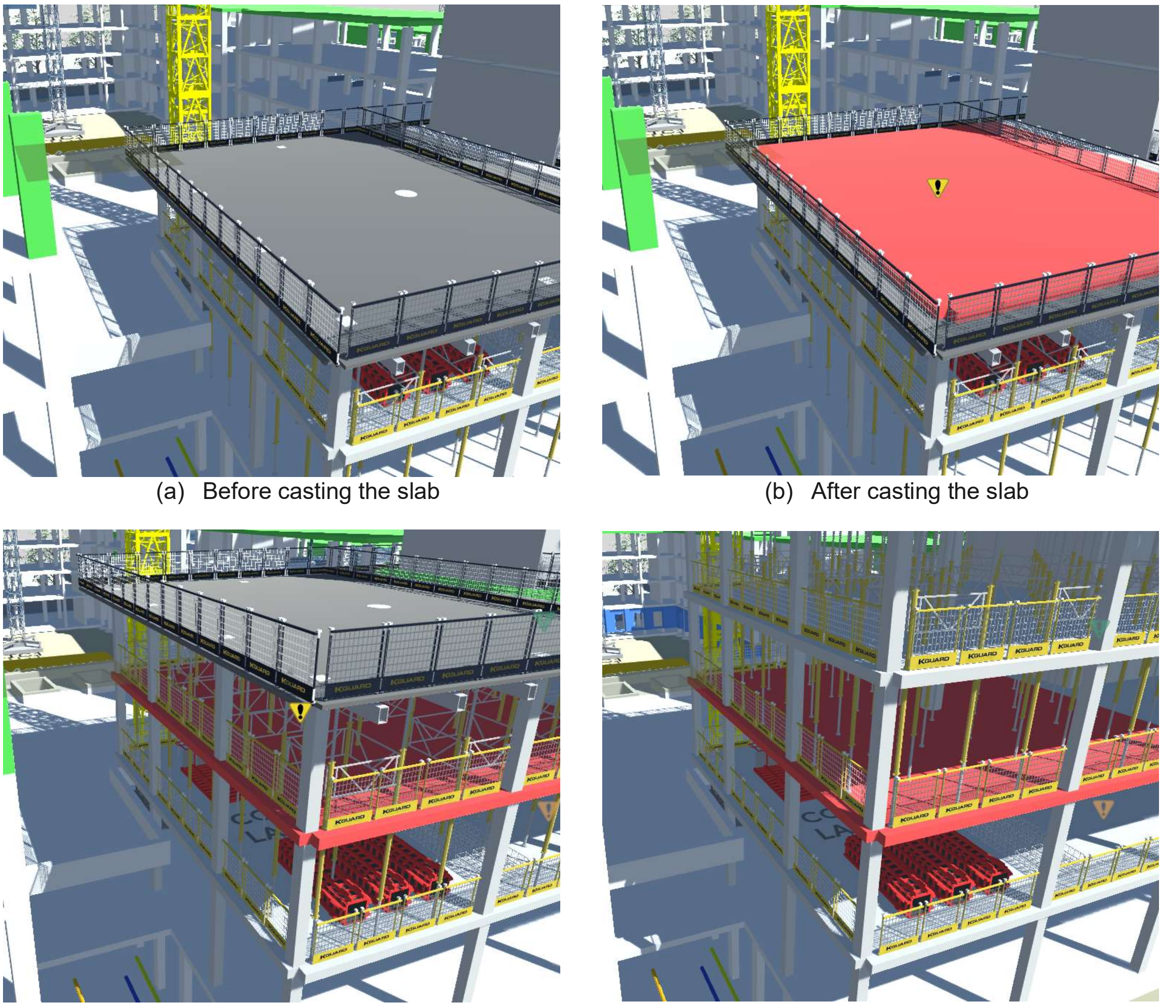
4.2 4D BIM as a means to visualise risks

The majority of the workshop participants agreed that some of the identified risks were not applicable throughout the construction phase of the modelled project. For example, the risk of falling into an excavation pit was no longer applicable once the excavation pit was backfilled or covered by the superstructure.

Motivated by this idea, the participants decided to provide start and end dates to risks where this condition was true. As a result, the indicative 3D pins associated to risks with start and end dates were only visible in the 4D model if the current date was in between the start and end date of the risk.

Figure 4 illustrates the visualisation of a risk scenario where the identified risk is related to the potential collapse of a reinforced-concrete slab if it is overloaded before the concrete reaches full strength. In this scenario, the start date is the date in which the slab is casted (b), and the end date is the date in which the curing process is finished (d). The indicative yellow 3D risk pin is only visible in between these dates.

The majority of the participants agreed that this approach was very useful. Particularly, from the perspective of temporary works planning. In the example illustrated in Figure 4, visualisation of the time-stamped indicative pin can help to understand when back-props need to be installed or removed. Additionally, it was found powerful to make the duration of risk exposure visible in a 4D environment.



(a) Before casting the slab

(b) After casting the slab

(c) Before curing is finished

(d) After curing is finished

Figure 4. Time-stamped safety risk pin associated to overloading a concrete slab, which is not visible in (a) before casting the slab and (d) after curing is finished; and visible in (b) after casting the slab and (c) before curing is finished

4.3 Barriers to adopting 4D modelling for safety management in construction

A comment in regards to a potential limitation of the approach was that as the construction programme evolves and the 4D model is updated, some of the identified risks would need to be updated as well. Therefore, it would be required to review all the previously identified risks to manually update them in addition to identify new risks that would arise as a result of the updated programme. This would require a significant amount of time and it's an error-prone process.

As part of the suggestions to improve future workshop sessions, one participant suggested that all the parties could have access to the 4D model before the session to prepare for the risk identification process. While the majority of the participants agreed that this would be ideal, concerns were also raised in regards to the fact that not all the participants would be able to use the software with the same level of skill and identified this as a limitation. As a means to overcome this limitation, it was decided to designate a person to navigate through the model on a shared screen during the workshop sessions.

5 Discussion

The results of this study suggest that 4D BIM enables a collaborative environment that promotes active engagement of those involved in the safety risk identification and treatment suggestion processes. This result addresses a concern shared by Zou et al. (2017) and Swallow and Zulu (2019), who suggest that a collaborative approach needs to be in place for 4D to succeed as a safety management tool.

Moreover, 4D BIM enables users to identify risks that could have been otherwise overlooked. This is in agreement with Choe and Leite (2017), who found that safety awareness is expected to increase when project participants visualise 4D models.

The results of this research also suggest that 4D BIM can be used to visualise risks that have an associated duration, which is particularly useful from the temporary works planning perspective. Recent studies have highlighted that the key advantage of 4D BIM is in visualisation (Swallow and Zulu, 2019).

6 Conclusions and future work

The main focus of this research was to explore how a 4D BIM can be used to support the traditional safety management processes at early design stages. Results reveal that 4D modelling improves the safety risk identification process by allowing stakeholders to visualise a particular point in time in the model and identify risks that would have otherwise been overlooked until later in the project. Thereby providing an opportunity to mitigate these risks with improved design, construction methods, and planning. Additionally, the 4D model provides a collaborative environment that promotes active engagement, which can improve the treatment suggestion process with a more in-depth discussion.

4D BIM was also utilised to visualise risks with an added time dimension by including time-stamped indicative pins to the 4D sequence. This capability was found to be invaluable, in particular from the temporary works perspective.

The workshop approach adopted in this research highlighted the value of involving project team members in 4D workshops as early as possible during the design phase of construction projects. 4D models that include detailed logistics, access, and safety equipment enable the early identification of safety risks and provides an opportunity to mitigate them.

Future work includes piloting the BIM Risk Library tool deployed in a 4D model in a live construction project. Lessons learnt from the workshop series will be applied to guide the pilot project participants as they incorporate 4D BIM with traditional safety risk management processes.

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