Integrating Building Information Modelling and Health and Safety Construction Phase

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Executive summary

Building Information Modelling (BIM) has many applications for health and safety during the construction process, and can support a range of activities. Four key areas have been addressed in this report, based on a review of international literature: 1) Hazard identification, 2) Scenario planning, 3) Communication and training, and 4) Monitoring and reporting.

While the development of BIM has specific needs and challenges to support each of these areas, the majority of the requirements and recommendations that can be drawn from the research literature apply across the board. Key elements include:

- Tools to support many of the uses of BIM for H&S are already available in the industry. Current BIM tools provide many opportunities for using BIM in health and safety applications; BIM is a powerful tool for communication and collaboration; this will have as much impact in H&S as it has in other aspects of BIM use in the design and construction process. Some limitations exist, however, in that not all tools are capable of interoperating directly with the BIM model or with other required tools.

- Immediate BIM-mediated H&S improvements can be obtained through a focus on people and practice.
  Ensuring modelling has been completed with health and safety needs in mind will extend the value of BIM for H&S. For example, an increased amount of detail is required in a model if hazards are to be represented effectively, including temporary works and construction equipment. The communication potential of BIM can be expanded through ensuring a greater range of people have knowledge of and access to the model, beyond the central management team to site workers and sub-contractors. Social and cultural factors will influence the acceptance and uptake of BIM tools, and workers will need training and support to become familiar and comfortable with the use of BIM in their daily activities.

- 4D BIM provides considerably more value in H&S activities than 3D BIM.
  Health and safety on site exists within a dynamic process; modelling ongoing site changes and stages using 4D BIM provides access to greater recognition of hazards arising in the process, and opportunities to plan for and manage them.

- BIM does not replace the expertise of safety specialists but leverages their knowledge and expertise.
  While some safety knowledge and documentation can be embedded in BIM models for use by anyone in the construction team, safety specialists are needed to identify key hazards, check automated processes, and make decisions on training and management. BIM is a support tool and may help extend their view of what is happening on a project, but their expertise is essential.

- More complex uses of BIM in H&S may require additional development and programming support.
  While many tools are available already and designed to interface with existing BIM software, linking BIM to other tools through VR, simulation or sensors is likely to require specialist programming skills. This may be achieved through interaction with software companies developing new BIM tools, or one-off programming tasks within a company or project. Ideally these programmers should also have construction knowledge or work closely with construction experts to ensure that any tools are relevant and useable by the construction team.

- A more automated use of BIM, for example in rule-checking and code-compliance activities, requires organisational and national development of knowledgebases.
  A national knowledgebase would allow code checking against national safety standards and practices. Also at a national level, data on the severity and frequency of different accidents or H&S breaches would be worthwhile, to allow projects to focus on the most notable causes of incidents and thus gain the biggest improvement from their actions. At an organisational level, companies should maintain their own knowledgebase to record lessons learnt regarding hazards arising and approaches for dealing with them. A cumulative approach would allow progressive improvement of safety practices and provide a valuable resource for other H&S initiatives, not just BIM.

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1. Introduction

1.1. Background

The hazardous nature of the construction industry is well recognised internationally; however, for the number of workers and projects in New Zealand, the number of injuries and fatalities experienced currently exceeds that of many other comparable countries (Lilley, et al. 2013). Various strategies and initiatives have been attempted to improve this situation over many decades, with a notable change taking place in 2016 with the introduction of the Health and Safety at Work Act 2015 (HSWA 2015). This legislation was not targeted specifically at construction but has shifted the emphasis within industry generally, from personal responsibility to a shared obligation on everyone involved to contribute to a safer working environment.

Another significant development in the construction industry is the growing use of Building Information Modelling (BIM), at all stages of the design and construction process. To date, the application of BIM has been largely focused on improving the production efficiency and cost-effectiveness of the industry, but its potential to contribute to health and safety improvements is now being recognised and extended.

1.2. Terminology

In this report, the term *BIM* has been used in the sense defined by Eastman et al. (2011, p16) as "a modeling technology and associated set of processes to produce, communicate and analyse building models", whereas *BIM model* has been used to refer to the product of that process, i.e., the model created using the process of building information modelling.

Essentially, BIM provides a framework which allows buildings to be represented, not simply geometrically, but using objects which have information attached to them. The amount of information included determines the value of the model and the uses to which it may be put. Commonly used BIM terminology used in this report includes:

- 3D BIM - the three-dimensional representation of a building, with associated attributes. A 3D BIM model provides the capability of visual representation of the building using static images, walk-throughs/fly-throughs, or integration into other interactive environments such as virtual reality (VR) and augmented reality (AR).
- 4D BIM - the 3D model with the addition of time-based information. The inclusion of scheduling data allows animations or simulations of the construction process.
- 5D BIM – a 3D or 4D model with cost data included.

Additional 'dimensions' of BIM are described differently by different organisations and are not widely adopted or recognised in the industry. In this report, health and safety has not been assigned a dimension but it has been assumed that health and safety information will be added to the BIM model at any level, depending on the project's requirements.

1.3. Sources and scope

This report seeks to make use of international research literature to identify uses of BIM to support Health & Safety processes during the construction stage of a project. It is based on a previously completed Systematic Literature Review (Guo, et al., 2022). Additional literature has been included beyond that covered in the SLR, to incorporate published findings on change management, knowledge management, and social impacts of BIM implementation, which were not considered in the initial work.

Many of the source documents in the systematic literature review report on research-based explorations that provide limited guidance on how these prototype systems would perform in a site application. Testing and validation are frequently carried out on very simplified building models, or on limited sets of elements, rather than full building models. The systems are also often set up and verified by researchers working from a theoretical position, not by industry professionals working in a typical construction environment. Questionnaires or interviews with practitioners are common as a form of industry validation, rather than hands-on industry application. These limitations are a necessary part of the development process, but, for the purposes of this report, case studies that represent a more industry-based application have been prioritised. Additionally, the references in the SLR span more than two decades of research. The case study examples selected for this report have been drawn from more recent publications, wherever possible.

1.4. Report structure

The discussion of the literature is organised by construction H&S activities. The following sections present a range of activities or applications where BIM provides an opportunity to improve health and safety during the construction stage of a project. Four activities have been identified as the focal areas for this report: 1) Hazard identification, 2) Scenario planning, 3) Communication and training, and 4) Monitoring and reporting.

Each of the activities is further divided into different aspects or approaches. A general description is provided for each of these, followed by a discussion of some illustrative case study examples or other relevant material drawn from the literature. As with most BIM uses, these activities are interrelated and are not isolated to a specific purpose, so a BIM model that is developed to achieve one application is likely to support one or more of the other applications. For example, a model that is sufficiently detailed to allow automated identification of hazards will also provide the basis for visualisation and simulation that can be used for hazard identification or training and communication purposes. As a result, some overlap can be found in the discussion so that each section can be read separately.

2. Hazard identification

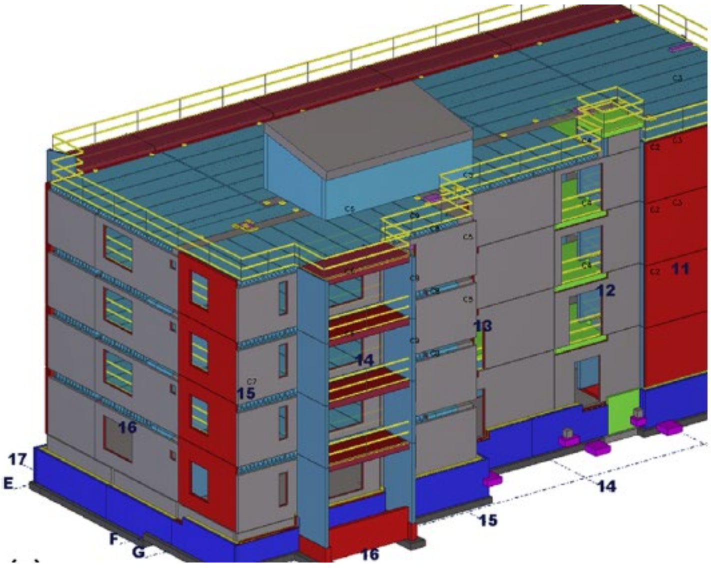
2.1. Introduction

Hazard identification and risk assessment is an ongoing activity throughout the construction process. It needs to respond to the constant changes taking place on site, and incorporate factors such as weather conditions, incomplete building work, temporary works and the movement of workers, materials and equipment.

2.2. Visualisation for hazard identification

In a traditional approach to hazard identification, a project representative with sufficient expertise would review the 2D construction drawing set, taking note of each element of the building that constitutes a hazard. BIM provides the option to complete this process with the improved visualisation offered by a 3D building model. Potentially, the BIM model could be linked to risk assessment data and safety knowledgebases specific to individual elements. The main advantage of 3D representation for identifying and evaluating hazards is to provide project participants with a clearer and more common understanding of the building (see Figure 1), instead of potentially different interpretations of what and where hazards exist, which may arise from different levels of skill in interpreting 2D drawings. The consistent understanding can transcend the varying levels of training and expertise that individual participants may have.

Figure 1. *3D visualisation showing failed wall openings and suggested guardrail protection*



Note: View of slab edge protection and wall opening protection, generated using a 4D model. From "BIM-based fall hazard identification and prevention in construction safety planning" by S. Zhang, K. Sulankivi, M. Kiviniemi, I. Romo, C. Eastman & J. Teizer, 2015, *Safety Science 72,* 31-45. (https://doi.org/10.1016/j.ssci.2014.08.001).

Extending a model to incorporate the construction schedule (4D BIM) provides an additional level of information to support hazard identification. Stages of the construction process may create additional hazards that will only be present for short periods of the process, for example unsupported structures during demolition, holes or uneven surfaces during excavation, or incomplete stairwells or skylights before edge protection is installed. These temporary hazards may become more easily recognisable when the construction process is seen in a dynamic view.

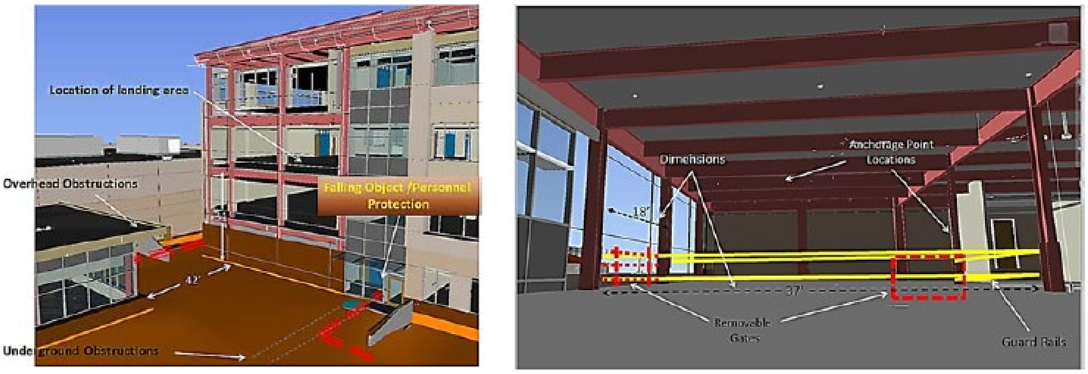
The addition of virtual reality (VR) or augmented reality (AR) to visualise a BIM model can improve the ease of navigation within a model and provide a more immersive and interactive experience for the user to identify potential hazards. With VR, users can use a headset and handheld controllers to move around and interact with the model. This can make it easier to manipulate the model or explore it from different perspectives, and intuitively understand the constraints or hazards of a building or space, such as overhead clearances or the need for edge protection. AR provides another level of interaction, where users can view the BIM model (3D or 4D) overlaid on the real-world environment, allowing them to better understand the relationship between the model and the actual site, or the building during its various states of construction. This can make it easier to visualise activities that will be taking place in a specific location, or the relationship between different parts of a building or elements of a site, and thus make the potential hazards clearer to users.

Game engines are also used to support BIM visualisations and can offer another approach for users to interact with the model to explore and identify potential hazards. They provide a powerful and flexible platform for creating interactive 3D models and offer an interface that users may be familiar with.

2.2.1. Case studies

Azhar (2017) describes the use of a 3D model to identify locations within a building project that presented a fall hazard, which was used by after a traditional 2D-based hazard identification process had been carried out. A number of elements that were not easily identifiable in the 2D drawings were picked up in the 3D representation, such as overhead obstructions, risk of falling objects, and obstacles to access or egress. A 4D representation of the project was also used to model excavation equipment, to identify any potential strike hazards such as nearby power lines or temporary structures. Interviews with project participants indicated that the 4D model proved helpful particularly to allow the involvement of stakeholders who were less familiar with health and safety tasks, or less able to interpret plans and written safety material (See Figure 2). Concerns that interviewees expressed included the extra cost involved to add the extra elements that were required in the BIM model to effectively represent safety aspects, and the need for close collaboration between the BIM modeler and site staff to ensure that the models were complete and accurate.

Figure 2. *Screenshots of BIM models used in morning safety meetings*



Note: From "Role of visualization technologies in safety planning and management at construction jobsites" by S. Azhar, 2017, *Procedia Engineering*, *171*, 215-226. (https://doi.org/10.1016/j.proeng.2017.01.329)

2.3. Automated rule checking

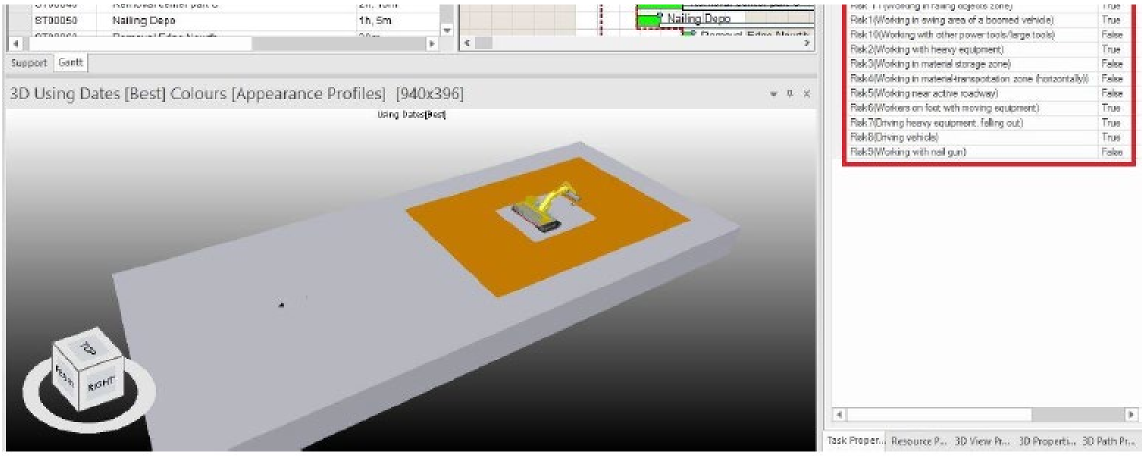
Clash detection is widely used early in the construction process to identify potential conflicts between different parts of the design before they occur on the construction site, so that they can be addressed and resolved without causing delays or disruptions to the project. The process is based on a set of pre-defined rules that are used to identify specific conditions in the model. In the case of clash detection, these rules are commonly focused on identification of specific places which overlap within the model, either through an overlap of objects or of required tolerances associated with an object. The same approach can be applied to identify health and safety hazards on site

Using appropriate rules for health and safety, automated rule checking may be used to check geometry and attributes of objects to identify potential risks to workers, for example locations where they may be at risk of falling from a height, such as open edges or unguarded stairwells. The system can then automatically generate alerts or notifications to warn of these hazards and prompt the implementation of appropriate safety measures, such as the installation of edge protection, such as guardrails or barriers, to prevent falls from occurring.

2.3.1. Case studies

Heidary et al. (2021) used a partially automated approach to identify a range of hazards on an apartment building project in Iran. The researchers focused on struck-by accidents, and identified a set of attributes that indicate the potential for this type of accident. They developed a set of algorithms that were implemented as queries for the 4D BIM model. The results from the queries resulted in notifications in the BIM model, to highlight the location of hazardous activities and allow the user to determine the appropriate measures to take in each situation.

Figure 3. *A view of a project's 4D BIM model representing the presence or absence of the hazardous attributes in the activity's property menu*



Note: From "Semi-automatic construction hazard identification method using 4D BIM" by M.S. Heidary, M. Mousavi, A. Alvanchi, K. Barati, & H. Karimi 2021 In *Proceedings of the International Symposium on Automation and Robotics in Construction (ISARC),* Vol. 38, pp. 590-597.

Zhang et al. (2015) took automated identification of hazards a step further, and incorporated rules for identifying potential solutions to the hazards identified. Using predefined rules, they queried the 4D model for potential for falls from height and institution of edge protection. They compared 4 different BIM tools that are in common use - Revit, Navisworks, Solibri Model Checker, Tekla Structures - and identified that none of them contained all the functionality that the task required. The functional requirements that they considered to be necessary were:

- Scheduling and simulation – to allow dynamic representation of the construction process over time
- Modeling – to allow updating of the model to include temporary objects required for fall protection, and to add the possibility of quantity takeoffs of these objects from the model.
- Site layout and visualisation – to include the site context in the model, because of the influence of site activities on safety
- Standard model format – used IFCs to provide the ability to exchange data between models and with specialist tools
- Rule-checking capability – to reduce the need for data exchange, and to allow integration of user-defined rules for the rule-checking process.

Although this project went beyond identifying the location of hazards and included automated development of potential solutions, Zhang et al. (2015) maintained that the use of automated hazard detection should not be used to replace the analysis and decision-making process of a safety expert, but rather to support their expertise. However, they pointed out that once a safety expert has established the rules and validated the output of the platform, the automated process allows the safety check to be updated as construction proceeds. This ensures that any changes in design or methodology can be quickly incorporated in the safety planning process.

2.4. Requirements and recommendations

The use of BIM as a visualisation tool for hazard identification is possible using currently available tools and technology; any changes required to allow this to take place are primarily focused on people and practice. Key aspects include identifying and modelling the level of detail required to provide effective representation of potential hazards, including temporary works, and deliberate use of the model as part of the hazard identification process.

Automated rule-checking is also possible using current technology, although as identified by Zhang et al. (2015), the full range of functions is not yet available using a single system. It may be necessary to use different software in combination to achieve the desired outcomes, and additional development may be required to implement suitable algorithms.

While automated rule checking can speed up the process of hazard identification, the modelling requirements are significantly increased to include elements that are not commonly included in a project model. These include temporary works and services, including site layout and operation, and more detailed representation of building elements such as connections between wall and slab, electrical services or seismic restraints.

The establishment of rule-bases to address standard H&S hazards would require significant expertise and time. Developing a rule-base for all H&S checks is likely to be too costly for any one company, and as there are legislative aspects to the rule-base a national approach would bring benefit to the whole industry. Individual companies could have in-house checking for a particular subset of hazards (e.g., falls from height) and to match their current practice.

A national approach will be necessary to source data for comprehensive hazard identification processes. For example, risk assessment requires detailed national information on accidents, their severity and frequency, to build the indices used to determine a project's risk profile. Similarly, individual companies, or even professions, may develop a knowledgebase of risks and their mitigations. Determining everything that could occur, could be planned for, and could be mitigated is likely to require input and agreement from experts across the industry. It is also a knowledgebase that would need constant maintenance as new hazards are identified, new materials and processes introduce new hazards, and alternative mitigation approaches are developed.

3. Scenario planning

3.1. Introduction

The scenario planning process begins during the design phase as part of the designers' safety in design (SiD) responsibility, so that safety aspects can be integrated into the development of the project design. Ideally, this should involve the contractor and other stakeholders in the project. However, the procurement process may not allow the contractor to be brought in at an early stage, and design consultants may lack the specialist knowledge of the construction process and in-depth awareness of construction alternatives that the contractor can bring once they are engaged on the project. SiD reviews continue to be important after the project has moved into the construction phase, to consider impacts of any changes in materials or design elements that may be necessary after a project is underway.

BIM provides the opportunity for testing multiple construction methodologies and sequences in a virtual environment, well before the process begins on site. This can help constructors identify complexities of the project in terms of space and project progression, and allows alternative solutions to be explored in a low-risk process. The goal of such a process is typically to produce a more constructible project and identify cost and time savings for the contractor, but less complexity in a project commonly translates to reduced risk from a health and safety perspective. Furthermore, scenario planning can be used specifically to focus on safety issues, as well as or instead of the consideration of cost and time aspects, to identify and eliminate or minimise risks for the constructors. For example, off-site manufacture may be explored for some elements to avoid hazards on site; working at height may be reduced through alternative construction sequencing; space and workspace conflicts may be identified and resolved ahead of construction.

Key applications of BIM in the scenario planning process include the use of 3D and 4D models as visualisation and communication tools within review and development discussions, process modelling using 4D BIM to explore dynamic scenarios, and augmentation of BIM using simulation tools or game engines to provide additional analysis or more interactive user interfaces.

3.2. Visualisation and communication

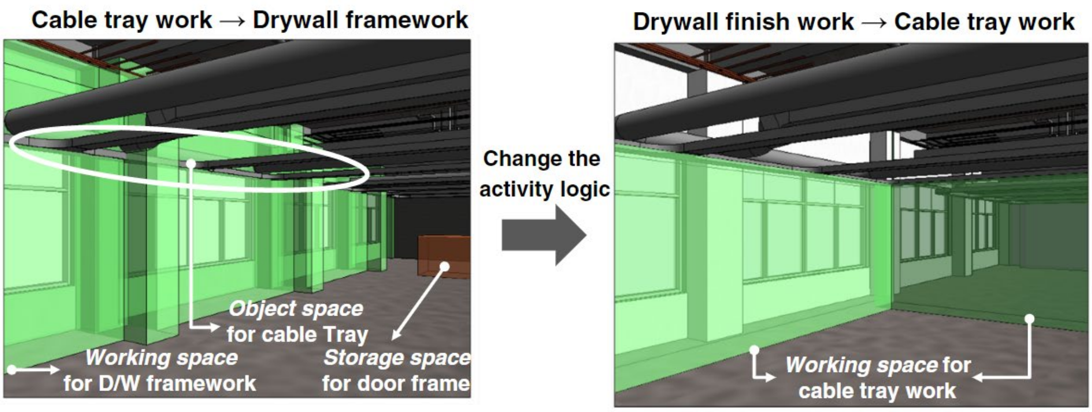
Visualisation is a fundamental aspect of BIM that allows all project participants to see the same representation of a building and make decisions based on a shared understanding. 3D modelling supports the use of snapshots and flythroughs of the building and site as a vehicle for designers and constructors to review decisions and investigate alternatives.

For more complex planning and decision-making, adding the time dimension and potentially a work breakdown structure to create a 4D model of the project can help identify potential conflicts or other issues with the construction process as the site and operations change progressively over the course of the project. This provides dynamic visualisations that allow project managers to plan and coordinate construction activities more effectively to improve safety on the construction site. For example, 4D BIM can be used to manage the space requirements of workers and equipment, by providing visualisations to help represent the most efficient routes for delivery and storage of materials and equipment onto the construction site, identify the work areas required for different trades, or test alternative scenarios to determine potential bottlenecks or clashes that will obstruct planned work.

3.2.1. Case studies

Workspace planning in construction is typically not a well-supported process (Igwe et al., 2020), and in most cases is dependent on the knowledge and experience of the individuals involved. To overcome this dependence, Choi et al. (2014) propose the development of a database to record information about the spatial requirements and associated properties of each construction method or material to be used in a building. This can then be connected to the BIM model to extract the necessary attributes to visualise workspace requirements and identify and resolve workspace problems (See Figure 4).

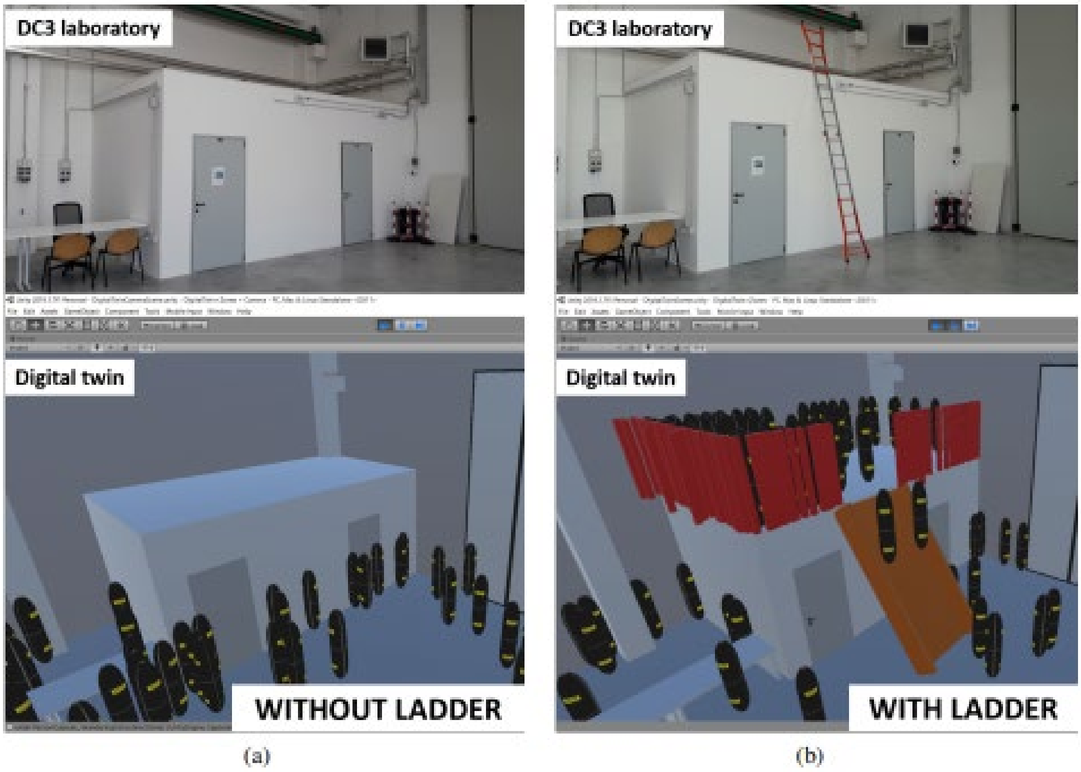
Figure 4. *Workspace problem identification and resolution*



Note: From “Framework for work-space planning using four-dimensional BIM in construction projects” by B. Choi, H.S. Lee, M. Park, Y.K. Cho, & H. Kim, 2014, *Journal of Construction Engineering and Management, 140*(9), Article 04014041. (https://doi.org/10.1061/(ASCE)CO.1943-7862.0000885)

A range of approaches to providing visualisations have been explored in the research community. Utilising game engines is one popular approach as commercial engines (e.g., Unity 3D) provide significant functionality to support movement and visualisation in realistic settings (e.g., including a physics engine to allow for realistic interactions between objects or virtual participants) and can load BIM data directly from all the major tools. This significantly reduces the effort involved in generating sophisticated visualisations for specific activities in a project. Messi et al. (2020) showed the ability to tie a simulation module detecting fall hazards to a digital twin of a building site to then visualise in near real-time where hazards need to be planned for. Figure 5 shows a scenario where the introduction of a ladder requires a fall prevention mitigation within a building.

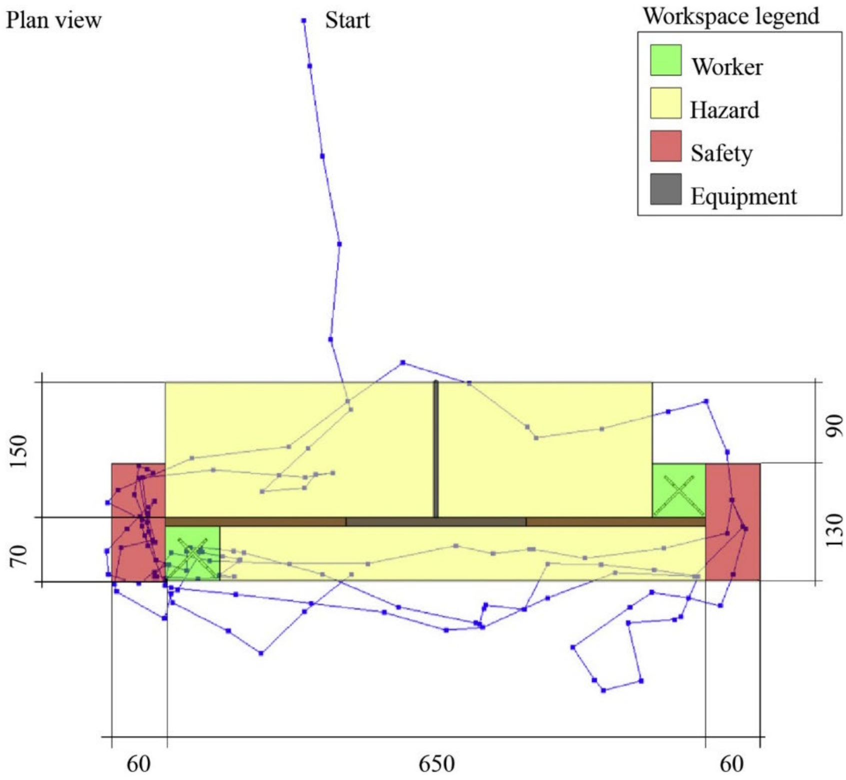
Figure 5. *Construction site for works at height recreated in a laboratory (top images) compared with its mirroring digital twin (bottom images). The floor above the changing room is not accessible (a) until the ladder has been placed (b).*



Note: From "Development of a twin model for real-time detection of fall hazards" by L. Messi, A. Corneli, M. Vaccarini, A. Carbonari, 2020, *Proceedings of 37th International Symposium on Automation and Robotics in Construction (ISARC 2020): From Demonstration to Practical Use to New Stage of Construction Robot,* (https://www.iaarc.org/wp-content/uploads/2021/11/ISARC-2020-Proceedings.pdf)

The fully immersive nature of Virtual Reality (VR) has also been identified as an important approach to providing realistic visualisations. VR environments can be populated from the 3D BIM model as well as being driven by the data in the BIM, including 4D BIM data and work breakdown structure information that they can contain. Not only does VR enhance the sense of being present on the site, it also supports realistic interactions with the objects, machinery, and other characters in the environment. For example, Getuli et al. (2020) used an immersive VR environment to track where workers would move on a site with various hazards (see Figure 6) and utilised this information for mitigations in hazardous areas.

Figure 6. *Location tracking of worker movement in a VR environment*



Note: Collection and transfer into the BIM workspace model of the worker's feedback and position tracking data. From "BIM-based immersive Virtual Reality for construction workspace planning: A safety-oriented approach" by V. Getuli, P. Capone, A. Bruttini, & S. Isaac, 2020. *Automation in Construction, 114*, Article 103160. (https://doi.org/10.1016/j.autcon.2020.103160)

3.3. Simulation

Whereas visualisation is primarily used within scenario planning to support communication and collaboration, simulation provides additional analysis through the use of software tools to identify potential issues and help improve the safety of the design or construction methodology. A BIM model typically contains most of the information required by many of the simulation tools available for construction H&S analyses (e.g., for an evacuation simulation). Where extra data is required, the BIM model can usually be augmented to capture the required information (e.g., via templates in Revit). Alternatively, the transfer tool can request input from experts during the transfer of data from BIM to a simulation, to ensure the simulation is able to proceed.

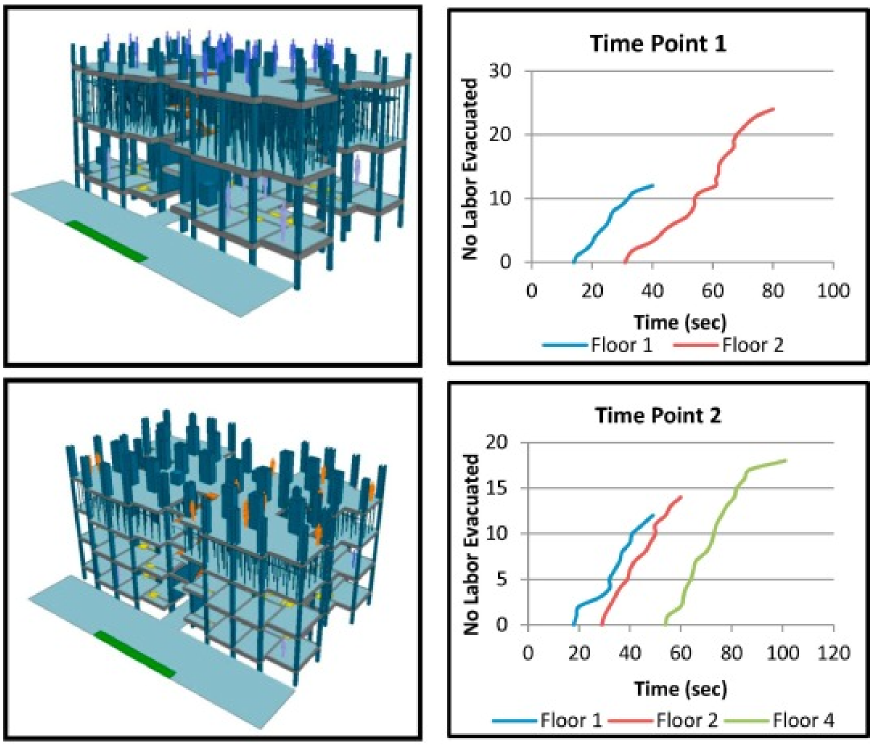
Simulation tools are available for a wide range of construction activities and through a link to visualisation approaches canvassed in Section 3.2 they can provide significant insight to H&S risks in construction. While generic simulation environments are available to perform analyses for a range of scenarios, these require high expertise to set up and interpret. However, bespoke simulation tools exist for analyses ranging from mobile crane operation, traffic flow and management, space utilisation and conflicts over time, evacuation time for a structure, smoke spread, etc.

3.3.1. Case studies

Simulation can be used to evaluate a construction site in the event of an emergency, such as a fire or natural disaster. By simulating different emergency scenarios, the effectiveness of evacuation routes can be evaluated, identifying potential areas of congestion or blockage, and assessing the impact of different emergency response strategies.

Marzouk and Al Daour (2018) tied an emergency evacuation model to BIM data to identify evacuation time for labourers in a building under construction across various time points in its construction (see Figure 7). Multiple scenarios were tested to allow comparisons at different stages of the project and using different construction methodologies. Key elements of the evacuation process could be identified from the simulations, allowing more attention to be paid to the planning, training and management around those aspects. For example, the stairs were a crucial factor in the evacuation process, so extra attention was paid during construction planning to keep them clear and free of obstacles. The simulations also identified that evacuation time was increased significantly with the presence of concrete activities, largely due to the increased number of workers on site at those times. Having this information before the works begin may provide the opportunity for specific training or other activities to be developed, or may prompt adoption of a different construction methodology.

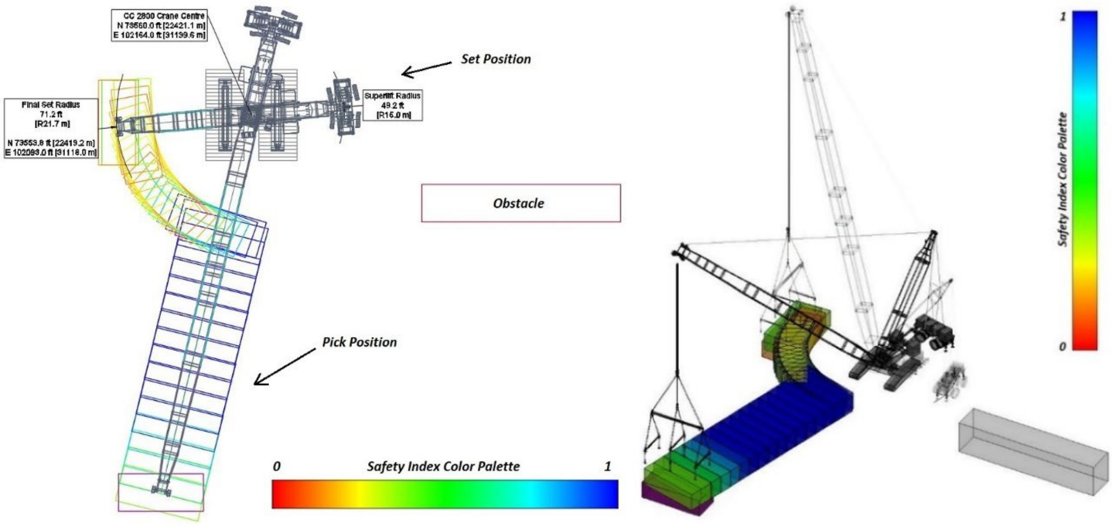
Figure 7. *BIM model over time alongside evacuation time*



Note: Collection and transfer into the BIM workspace model of the worker's feedback and position tracking data. From “Planning labor evacuation for construction sites using BIM and agent-based simulation” by M. Marzouk & I.A. Daour, 2018. *Safety Science, 109*, 174-185. (https://doi.org/10.1016/j.ssci.2018.04.023)

Tak et al. (2021) demonstrated the ability to tie safety index calculations with mobile crane operations for work on site, drawn from 4D BIM data. In a case study with two cranes operating on a site, they identify potential interference in operations, the scheduling of equipment movement and safety impact, as well as the locations on site most impacted by crane movements (see Figure 8). The project used Navisworks to take advantage of information already included in the BIM model, in combination with the outputs of specialised crane planning and optimisation systems. Together, this information provided richer and more accurate models of crane use than would have been possible with traditional representation in 2D or 3D.

Figure 8. *Safety index values for selected lift operations*



Note: Color-coded plan and isometric views of the selected lift operation. From "BIM-based 4D mobile crane simulation and onsite operation management" by A.N. Tak, H. Taghaddos, A. Mousaei, A. Bolourani, & U. Hermann, 2021 *Automation in Construction, 128, Article 103766.* *(https://doi.org/10.1016/j.autcon.2021.103766*)

3.4. Requirements and recommendations

The use of 3D BIM as a visualisation and communication tool for scenario planning enables a collaborative process between contractors and designers to improve construction safety while maintaining design intent. It allows changes to be worked through by the parties involved, while rapidly providing feedback of the impact of any changes on the appearance and function of the building, through a visual representation.

Greater functionality for the construction team can be obtained once dynamic modelling is introduced with 4D BIM. This allows a time-based simulation of the construction process which can be useful to identify potential conflicts or issues that may arise, such as the potential for workers on different trades to be in the same area at the same time, or the risk of heavy equipment being used in close proximity to workers. To increase the value of BIM in this process, detail regarding construction equipment, materials, and labour need to be incorporated. Temporary structures and plant such as cranes, boom lifts, and scissor lifts are not typically part of a BIM model but need to be considered to allow workflow and potential clashes to be planned for. Tools such as cmBuilder make use of a BIM model but provide additional libraries of temporary works and simulation of site logistics which allow representation of construction activities without the need for modelling expertise.

Game engines and VR environments are also making it easier for non-specialists to visualise and interact with digital analogues of a construction project across time, though developing a model for use in these environments currently requires software developer skills. New tools on the market such as Urban Circus reduce the expertise needed to provide these visualisations and active scenarios.

Rule-checking can be improved through the use of a database that records hazards and mitigation strategies, and tracks the effectiveness of different prevention strategies. This information can then be used to inform the safety planning for future projects, helping to ensure that similar hazards are identified and addressed in a consistent and effective manner.

A large number of simulation tools and analysis systems are available for H&S in construction. Only a modest number currently interface directly with BIM, though it is possible to build translators which extract the BIM data necessary for such tools. This is a highly technical skill and not readily available in the construction industry. Working with software developers to support this functionality from BIM would unlock the power of scenario planning and simulation for construction across the industry.

4. Communication and training

4.1. Introduction

Since its introduction, BIM has been hailed as a tool for communication and collaboration. It is well established that BIM allows different members of a construction team to work together and share information more efficiently. This can help to improve communication and coordination among team members, reduce the potential for errors or misunderstandings, and ultimately lead to better outcomes. BIM is particularly valuable within the area of safety communication, where the ability to convey information visually can provide a more inclusive approach to explain and explore safety issues with stakeholders. It can help overcome language barriers and aid understanding of project participants with varying levels of skill or experience.

Training can also be supported using BIM. Work environments and constraints can be modelled, including existing or potential construction hazards. Simulated activities in a virtual environment provide the possibility for participants to explore a project virtually, without putting them into hazardous situations. This can help develop better understanding of potential hazards and safe work practices.

4.2. Visualisation

The visualisation opportunities offered by BIM have many applications in the context of safety communication and training. BIM visualisations can be used to support safety communication in a wide range of situations, such as informing site staff about safety requirements or warning about risks. The BIM model provides a representation of the site and building that can be used for managing and sharing up-to-date plans and site status information, to facilitate collaboration with workers in safety planning and decision-making. Visual aids such as photographs and videos can be created to educate workers or visitors on the importance of safety, potential consequences of unsafe practices, proper use of safety equipment and procedures. Images can support or replace verbal or written instructions or information and help to overcome language barriers that are common on construction sites with a multi-cultural workforce. Virtual walkthroughs of a site at different stages of the construction process can be used for site inductions or toolbox talks to highlight potential hazards, required personal protective equipment (PPE) or other safety equipment, and identify safe work practices. Difficult operations such as the movement of heavy equipment and materials can be portrayed using images or videos drawn from the model, to identify potential hazards and plan safe lifting and transportation strategies.

4.2.1. Case studies

Ahn et al. (2020) compared safety knowledge and training engagement between a group of workers trained using conventional training methods (lectures supported by slides and videos) and a group trained using 3D modelling views and simulations of the building on which they were working. Both training approaches made use of the same training room and equipment. They concluded that workers who experienced training using the BIM model showed better understanding of the safety issues and appropriate behaviours than those who were trained using conventional methods. An analysis of workers' characteristics indicated that this improvement was not limited by age or experience. The ability to customise training information to the specific building under construction proved more engaging for participants; however, the researchers found that a lack of modelling resources for elements such as construction equipment, scaffolding and other temporary works was a limitation in providing the level of realism that was possible with photographs and videos used in traditional training materials.

4.3. Virtual reality and immersive training scenarios

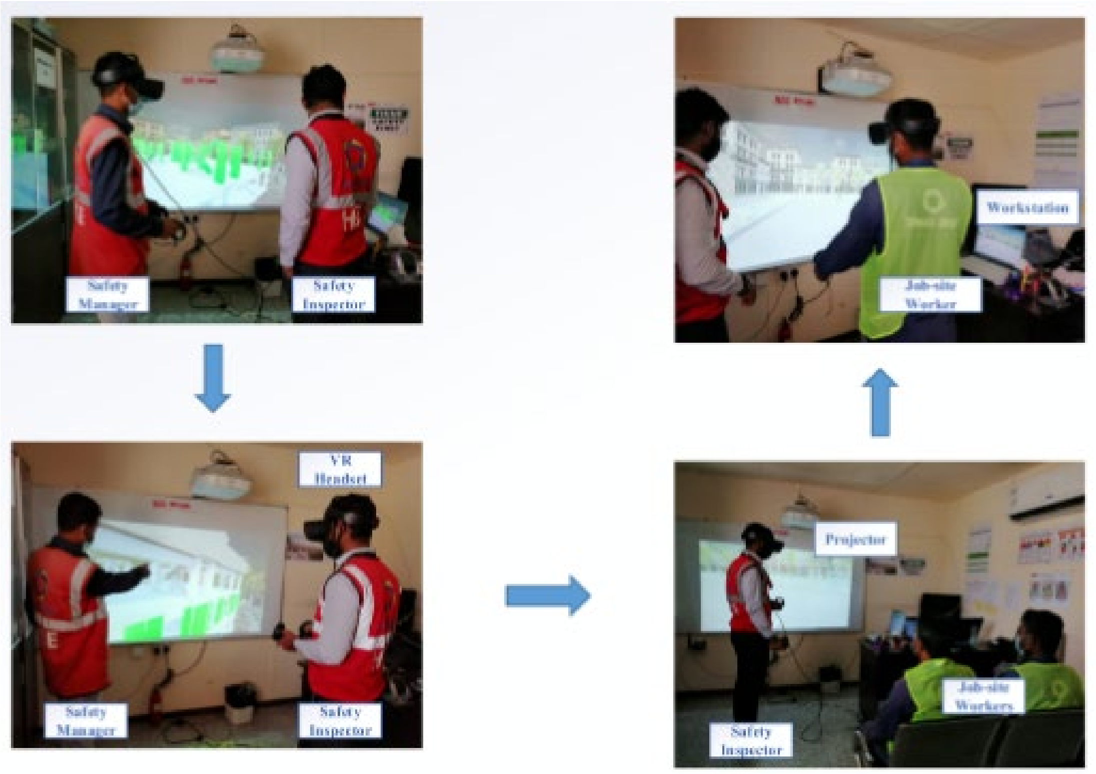
The use of BIM and virtual reality in safety training involves the creation of scenarios for trainees to experience potentially hazardous activities in a safe environment. The types of scenarios can be tailored to the needs of a particular project: virtual walkthroughs of the construction site can provide an induction experience which allows site staff to familiarize themselves with the layout and be aware of potential hazards; emergency situations, such as fires or earthquakes, can be simulated and prepared for without interrupting site activities with full scale drills to practice evacuation and other emergency responses; hazardous work environments, such as working at height or with dangerous materials or equipment can be simulated so that workers are prepared for the experience before they encounter it on site.

The development of appropriate scenarios is constrained by the availability of a suitable model, and the skills and knowledge of expert staff available to determine the relevant factors to be included in the simulation. Mo et al. (2018) noted that while VR and game-based accident simulators can improve worker engagement and provide effective training, this may be undermined if important details or elements are not included in the training module. Scenarios are often limited by the experience or expectations of the training designer, and unless experienced safety experts are involved in the development process, key aspects may be overlooked. To overcome this limitation, a national database of US construction industry fatalities was used to identify the most common variables in fatality accidents, for inclusion in training scenarios. This possible over-reliance on digital skills rather than construction knowledge and experience is an issue identified in a range of different BIM contexts, and highlights a lack of practitioners who have both sets of expertise.

4.3.1. Case studies

Afzal and Shafiq (2021) used VR interaction with a 4D model to support training activities with workers from multi-lingual backgrounds. (See Figure 9). Using VR headsets, workers were given the opportunity to explore a range of risk scenarios where they experienced simulated threats to their safety. They were then able to propose the actions they would take in each situation to remain safe, and explore action plans developed by the site safety experts. The team found the visualisation activity very beneficial for sharing knowledge and improving safety awareness, but considered that more work is necessary before this approach could be used as a matter of course in construction safety training. The primary challenge identified in this exercise was the variability of the model representations of different elements. The level of detail throughout the model was not consistent, so it could be possible for trainees or even safety experts to overlook aspects of safety because they were not expressed in the model. The amount of time required to develop the 4D simulation and associated scenarios was also considered a significant barrier. The researchers also noted that the VR training environment should be considered in addition to the safety expert on site, and did not replace their involvement in training or safety planning.

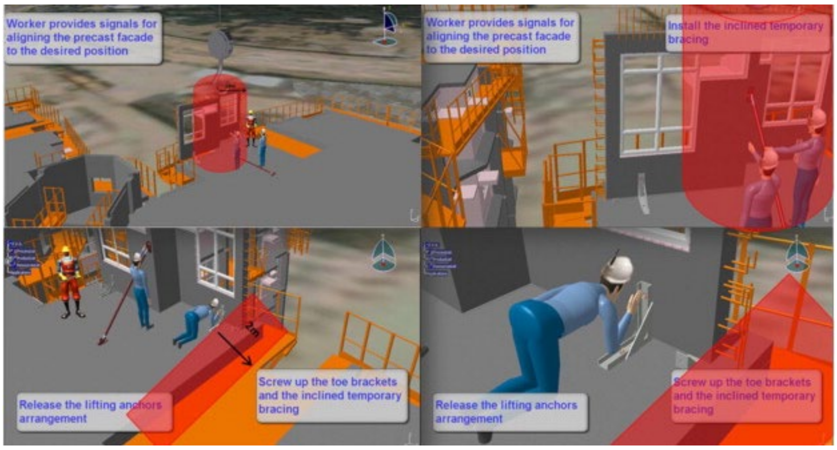
Figure 9. *Interactions between safety experts and workers using VR*



Note: From "Evaluating 4D-BIM and VR for effective safety communication and training: A case study of multilingual construction job-site crew" by M. Afzal & M.T. Shafiq, 2021, *Buildings*, *11*(8), Article 319. (https://doi.org/10.3390/buildings11080319)

Li, et al. (2015) took a more immersive approach to training, using physical elements in conjunction with VR to train workers in the installation process for a precast façade element (see Figure 10). The simulation also included monitoring of the construction activity with real-time warnings or alerts for any hazards that were encountered. This real time feedback, in combination with a post-event review, allowed workers to improve their performance and respond appropriately to hazards. By gaining familiarity with the task in a virtual environment, workers are able to learn and make mistakes in a low-risk setting, and to gain an awareness of the types of hazards they will encounter on the construction site. As well as safety benefits, this immersive training experience also has productivity benefit, as workers are faster and more efficient at their task once on site, and site activities are not held up by inexperienced workers.

Figure 10. *Training session to place a precast facade element using a virtual construction simulation*



Note: From "Proactive training system for safe and efficient precast installation" by H. Li, M. Lu, G. Chan, & M. Skitmore, 2015. *Automation in Construction, 49*(PA) 163-174. (https://doi.org/10.1016/j.autcon.2014.10.010)

4.4. Requirements and recommendations

BIM is valuable as a resource to support training and communication activities, and can be used to capture and share the knowledge of safety experts. The use of simulations or flythroughs based on information and images relevant to the specific project allows hazards and safety expectations to be communicated explicitly to workers, and the visualisation capacity is useful to overcome misunderstandings that may arise due to language diversity within a construction workforce.

However, BIM does not replace the expertise and experience that safety specialists bring to the role. Their input is essential in determining how and for what purposes visualisations or VR should be used, what scenarios or should be represented, and what key components need to be included. Digital specialists may be necessary for the modelling and programming activities to establish the functionality of the model uses, but the relevant safety knowledge needs to be the driver for the application. However, through the use of BIM tools for safety training, a company may be able to develop a cumulative record of safety knowledge and approaches that will assist with knowledge transfer from one project to the next. As identified in several other safety applications of BIM, this process could be accelerated through the creation of a knowledgebase to record hazards encountered on a project and responses to them.

Model quality directly affects the value that BIM brings to training and communication: building elements that are not modelled are not available for visualisation or training use. However, many of the elements required for safety training, in particular temporary works such as construction equipment and scaffolding, are not commonly included in a BIM model. As a result, additional effort needs to be invested into model development, or BIM-based training needs to be supported by more traditional methods using standard videos or images.

The use of BIM and virtual reality to provide an immersive training environment offers significant benefits for workers who can grasp concepts more easily with the visualisation tools available with BIM, or gain experience of hazardous operations in the low-risk virtual environment of VR. However, the use of this technology may be challenging for workers who are not familiar with it, and some may be unwilling to engage. As a consequence, training in BIM and VR tools may be necessary before the benefits can be realised.

5. Monitoring and reporting

5.1. Introduction

Monitoring of construction safety covers a variety of aspects during the construction phase of a project. Regular inspections of the site are common to check workers' adherence to safe practices, as well as to ensure appropriate safety measures are in place and functioning as expected. Aspects of the physical environment are also often monitored to identify potential hazards or deviations from the norm, including performance of construction equipment, structural integrity of building elements, changes in ground conditions or presence of dangerous substances. Many of these safety monitoring and reporting activities can be carried out using the BIM model as a reference, with the addition of sensors, cameras, laser scanners or other equipment to provide a connection between site conditions and the model (Asadzadeh, et al., 2020).

5.2. Site inspection

Site inspection using BIM involves a comparison of worksite conditions against the BIM model to identify differences and discrepancies. This allows identification of areas where works are being carried out, for example to ensure appropriate exclusion zones are established, or to identify whether protective barriers are in place. Site inspection is typically undertaken using cameras or laser scanners, which may be mobile or mounted in fixed locations. It can be based on still images, videos or point clouds, viewed in real-time or downloaded later.

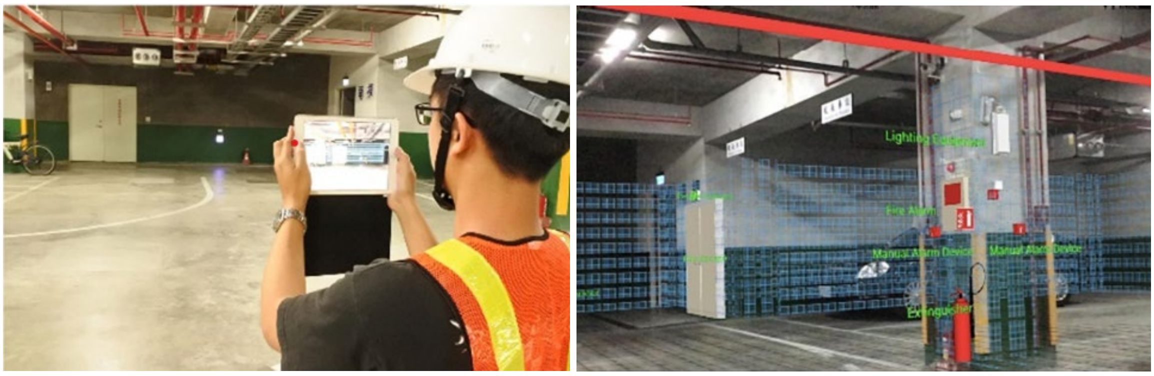
Data associated with site elements that have been recorded in the BIM model can be accessed on site through headset systems or on devices such as tablets or smartphones; this would allow users to retrieve safety certification of equipment such as cranes, scaffolding and electrical equipment to identify whether it has been inspected and deemed safe for use, and any conditions or qualifications required for safe operation. Similarly, areas designated for specific purposes can be checked against the model to determine whether appropriate certification is in place, for example in areas where Hot Works are permitted or prohibited, or where hazardous substances are stored.

BIM can be used in conjunction with headset cameras to create an augmented reality experience for site inspections. This allows construction professionals to overlay digital information from the BIM model onto their view of the physical building in real-time, as they move around the site. Safety elements such as fencing, warning signs, protective barriers and covers can be inspected and compared against the details in the model, to ensure planned safety measures are being implemented appropriately on site. Kolaei et al. (2022) note, however, that an augmented reality approach of this type may bring with it additional safety challenges, due to the cognitive load and potential distraction involved. Remote inspection using UAVs (unmanned aerial vehicles, or drones) or ground-based robots provides another method of carrying out site inspections, that allows the operators to be off site and thus avoids the risk of divided attention on site.

5.2.1. Case studies

The use of BIM and augmented reality for site inspections was investigated by Chen, et al. (2020) in the context of fire safety equipment (FSE). The preliminary stages of this project required the design of a formal system of inspection for FSE, followed by the construction of a database of the information required for FSE inspection and maintenance. Data was exchanged between the BIM model and the inspection database using the COBie format. On site, the operator used a mobile device to view the site environment overlaid by data from the BIM model and FSE database. This identified the expected location of equipment and provided annotations of the parameters that required inspection. The operator could also access the database directly to add notes connected to the equipment location and identification codes (see Figure 11). The validation study used undergraduate and graduate students as the test operators, and found that while the system was a useful support for anyone carrying out the inspection, it still required a knowledgeable and experienced operator for it to be effective.

Figure 11 *Use of augmented reality visual aid on site; view of annotated overlay*



Note: Demonstration of BIM-AR system for fire safety inspection. From “BIM-based augmented reality inspection and maintenance of fire safety equipment” by Y-J. Chen, Y-S. Lai & Y-H. Lin, 2020. *Automation in Construction, 110,* Article 103041. (https://doi.org/10.1016/j.autcon.2019.103041)

Several theoretical case studies provide examples of the use of BIM in conjunction with UAV-mounted cameras to allow remote monitoring or site inspection. Alizadehsalehi, et al. (2020) demonstrated that UAVs could be used to enable real-time images, video and point-cloud data to be transmitted for examination without the need for a safety specialist to be present on site. The 3D BIM model would be used to identify locations considered of most value for inspection, for example where significant hazards were present or where current site activity was concentrated. The images recorded could then be compared back to the BIM model to allow safety measures to be analysed and any deviations identified. While a 3D model allows initial locations to be identified, an accurate 4D model is necessary for the work-in-progress data from the UAV to be compared with work-as-planned. Key advantages noted in using this approach for inspections were that the use of UAVs provided access to areas of the site that could otherwise be difficult to observe, and that it reduced the workload of the safety specialists. Challenges included the impact of weather conditions on the use of the UAV, and the need to negotiate restrictions on UAV use. Alizadehsalehi, et al. (2020) further noted that the process of checking data against the BIM model could be automated. Johansen, et al. (2021) tested a process of automating the inspections of safety railings by mapping point cloud data against the BIM model and checking for discrepancies. They concluded that this approach had great potential in reducing the time and labour requirements of such inspections. However, neither of these examples tested their processes in live projects.

5.3. Activity monitoring

Video and visual recognition technology, or tracking and sensing technology such as RFID (radio-frequency identification), GPS and other sensors, can be used to monitor a range of site attributes, including vehicles and other equipment, workers, materials and the physical characteristics of the site itself. Aspects that are most commonly monitored are location and movement, but with the use of appropriate sensors other aspects can be included, such as noise levels and vibration.

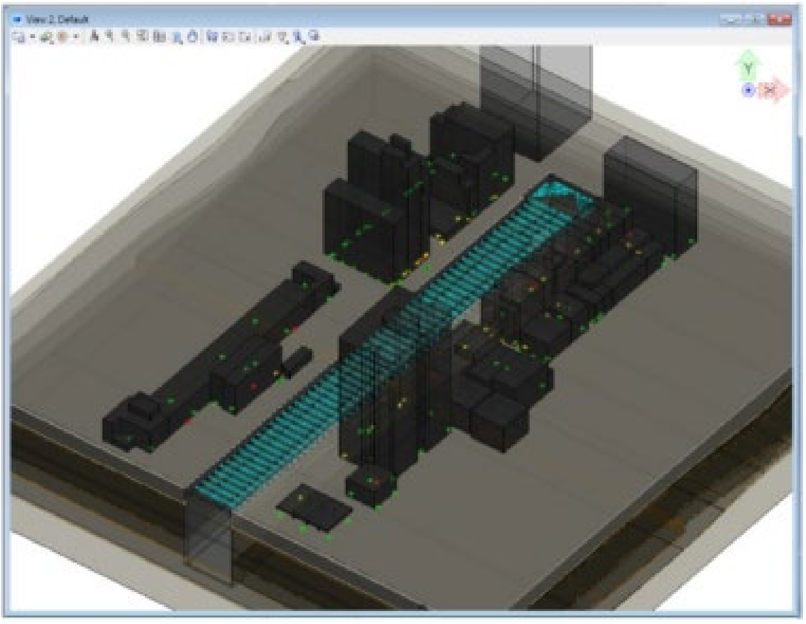
Activity monitoring can be preventative, to recognise developing or potential hazards before they occur; or reactive, to correct unsafe actions or events when they are identified. Where technology-based monitoring is used at an individual level to observe and correct workers' behaviour, end-user acceptance and trust become key factors, with workers concerned about issues of security and privacy (Häikiö et al., 2020).

5.3.1. Case studies

A form of activity monitoring is explored by Chen, et al. (2016) in the development of an AR user interface for crane operators. BIM is integrated into the interface which provides users with real-time images of the site, overlaid with the BIM representation. The use of the model provides information on objects lifted by the crane such as size, weight and intended location, and calculates a collision-free lift path for the operator. The system also includes automated risk detection to alert the operator of any dangerous situations that arise, for example if a potential collision is detected, if the crane is overloaded or if wind effects become too strong for safe operation. The system performed well in a simulated construction environment, with project participants reporting good useability and improved response to potentially dangerous situations. However, this interface was only tested in laboratory conditions, not on a real construction site.

Wu et al. (2015) used sensors on site to monitor movement of surrounding buildings, retaining walls and ground levels, as part of a deep excavation project. These sensors were linked to the BIM model to provide a user interface that displayed whether the status of specified variables remained within acceptable limits. The data from each sensor was stored in a database that was linked to the BIM model. The monitoring instruments were represented as objects within the BIM model which, as well as providing a simple visual reference using red, amber and green indicators, could also be interrogated to provide more detailed data on each sensor. This allowed centralised monitoring of site conditions and provided users with a visualisation of risk locations and potential hazards (see Figure 12).

Figure 12. 3D building model including visualisation of sensor indicators



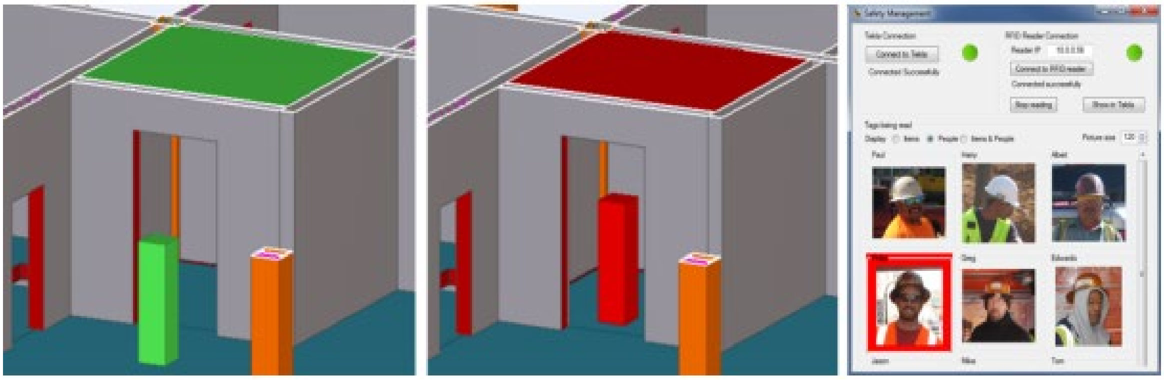
Note: Overall monitoring data in a 3D visualisation environment. From "A BIM-based monitoring system for urban deep excavation projects" by I-C. Wu, S-R. Lu & B-C. Hsiung, 2015. *Visualization in Engineering, 3,* Article 2 (2015). (https://doi.org/10.1186/s40327-014-0015-x)

BIM can also be used in conjunction with sensors for monitoring of safety at an individual level. Costin et al. (2015) used RFID tracking to manage worker locations and control access to restricted zones. Project managers set up rules in the BIM model regarding access requirements or authorisations to various zones within the site. Authorisations may be linked to training or certification, or to worker role. If a worker entered a restricted area without the necessary authorisation, an alert would be sent to the project manager identifying the location, the worker's identity, and the nature of the violation (see Figure 13).

This or similar technology could also be applied to creating a record of worker movements on a site, allowing analysis of access and transport routes which could be used to reduce unnecessary movements or redirect workers away from hazardous activities. Golovina et al. (2016) used GPS tags as the basis for this type of analysis. Operator blind spot areas were mapped for heavy equipment on site (specifically a skid steer loader) and overlaid in a BIM model. Workers in the area were monitored with GPS tracking, as were equipment movements, to help determine where exclusion zones were necessary to prevent workers from being struck. The visualisation was also used to support worker training so that the risk of blind spots could be made explicit. Park et al. (2017) carried out a similar project using Bluetooth low energy (BLE) technology to monitor workers' location on a construction site. Worker movements were visualised in the BIM model in relation to hazards that had been previously identified, to assist safety experts in site planning and to aid in training activities for workers.

Technological challenges of any such system include setting up the necessary tag reader infrastructure on the site in appropriate locations and issuing all staff with tags, as well as setting up and managing zones or site changes for monitoring within the BIM model. Cultural factors would also need to be considered. Costin et al. (2015) noted that workers were initially hesitant and concerned about how the system would be used. Seminars and training were needed to educate workers on the purpose of the system and to emphasise that it was intended to improve safety and security of the project, rather than close monitoring of individual workers.

Figure 13. *Visual alert generated when an unauthorised worker enters a hazardous workspace*



Note: Model section showing change in representation when a worker enters a restricted area without authorisation. From "A BIM-based monitoring system for urban deep excavation projects" by A.M. Costin, J. Teizer, & B. Schoner (2015). RFID and BIM-enabled worker location tracking to support real-time building protocol and data visualization, *Journal of Information Technology in Construction (ITcon), 20*. 495-517 (http://www.itcon.org/2015/29)

Dong et al. (2018) explored the use of BIM-integrated sensor systems to check worker behaviour as well as location. Zones within the BIM model of a construction site were defined in which workers were required to use specific PPE, in this case safety helmets. Workers were assigned mobile locator tags that linked to the BIM model to identify the position of the workers on site (see Figure 13). If a worker entered one of the previously specified hazard zones, the system provided a warning. Following a designated response time, the system then checked the status of a pressure sensor mounted in the worker's safety helmet. If the sensor indicated that the helmet was not being worn and the worker was still located within the hazard zone, a safety violation was recorded. In this trial, video recording of the site was used to validate the sensor indications. Dong et al. (2018) suggested that the system could be used purely as notifications to workers to remind them of safety expectations, or could form the basis of a reward or penalty system intended to influence workers' behaviour. The trial did not include an active response to safety violations beyond the automated warning, but recorded performance over time to support training and goal setting for site safety.

Figure 14. *Monitoring misuse or non-use of PPE*

Note: Real time location of the worker connected with virtual site model with hazard zone shown by red shading. From "Building information modeling in combination with real time location systems and sensors for safety performance enhancement" by S. Dong, H. Li & Q. Yin, 2018. *Safety Science, 102,* 226-237. (https://doi.org/10.1016/j.ssci.2017.10.011)

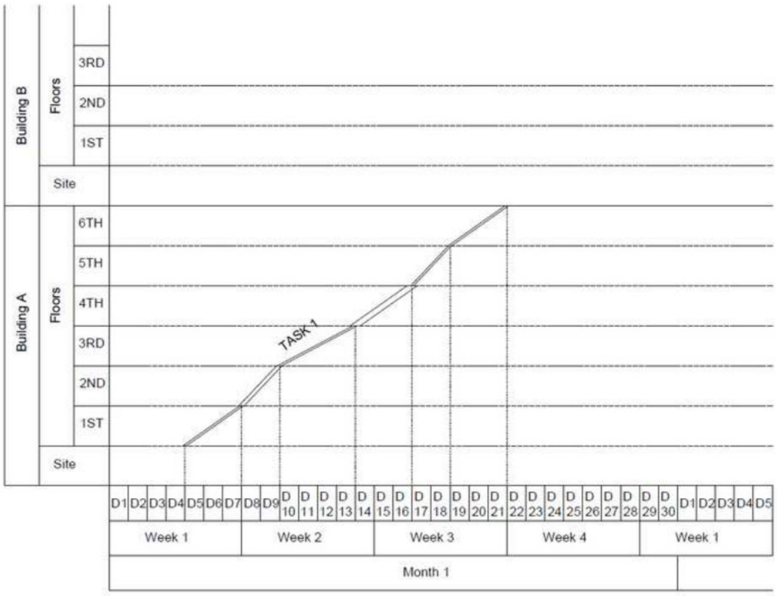
5.4. Managing hazard exposure

Sensors can be used to record the amount of time that workers spend in particular zones. Costin et al. (2015) presented this function as a tool to support billing and record keeping for project productivity, it also has safety applications. If environmental conditions in some locations require workers to limit their exposure, for example because of hazardous conditions such as noise or vibration, this system allows tracking in the BIM model.

5.4.1. Case studies

BuHamdan et al. (2021) used BIM to support the management of hand arm vibration syndrome (HAVS) on a project which required extensive use of hand tools to fix CRT panels. While a lot of the research process was concerned with using BIM to identify and minimise HAVS risk in the design stage, through visualisation and simulation (see section 3), they also introduced a monitoring process to manage the exposure of workers to this hazard. The likelihood of a worker developing HAVS is cumulative, and the amount of time spent using handheld power tools is a key risk factor. Accordingly, the location, specific hazards and hazard intensities for power tool use for a particular part of the construction process were linked to time, using a location-based hazard distribution diagram. This uses 4D BIM data to map the progress on site for each activity and allows adjustment of number of workers or allocation of work, so that the amount of time a worker spends using tools in repetitive or high-risk tasks can be monitored and managed. This project used secondary simulation, but the authors suggested that this could be simplified if BIM objects could have a hazard variable attached, in this case for HAVS but potentially for any hazard, that would allow calculation of the location diagram directly from the BIM model. Constraints of this approach are that it requires the construction schedule to be prepared using the location-based scheduling methodology (see Figure 15); it also requires the project team to include programmers who have appropriate expertise for the scheduling and simulation activities.

Figure 15. *Location-based hazard distribution diagram*



Note: Modified version of project flow-line presenting the identified hazards and their intensities. From "Developing a BIM and simulation-based hazard assessment and visualization framework for CLT construction design" by S. BuHamdan, T. Duncheva, & A. Alwisy, 2021. *Journal of Construction Engineering and Management, 147*(3), Article 04021003. (https://doi.org/10.1061/(ASCE)CO.1943-7862.0002000)

5.5. Requirements and recommendations

Use of BIM with additional technologies to manage safety inspection or monitoring on site has been widely demonstrated but the majority of published case studies appear to be based on theoretical or simulated environments rather than use in practice, limiting the lessons which can be drawn from the research. Despite this shortcoming, the examples make clear that these technologies are effective to support safety experts, rather than replacing them on site. Experienced safety practitioners are needed to define the elements requiring inspection or monitoring, identify hazards or locations of interest in the BIM model, and to analyse the data produced by on site monitoring systems.

A variety of sensing technologies are available for location monitoring of workers and equipment, including RFID, GPS and Bluetooth. The specific conditions of the construction environment will influence the choice of technology; for example, GPS does not work well indoors; and many materials will attenuate transmission of RFID. For most of these technologies, additional infrastructure such as readers, antennas, and cables are needed to set up the system. Similarly with sensors for other parameters, the conditions on site will require consideration of factors such as sensor ruggedness, range, and infrastructure required. In most cases, specialised programming will be required to link the sensor output with a BIM model for a visual representation.

All active site monitoring requires constant updating of the BIM representation of site conditions, to provide accurate representation of site geometry, location of hazards or designated zones. This is likely to require modelling at a more detailed level than is commonly used, particularly in depicting changes over time as construction activities are in progress.

Where BIM-based monitoring systems are used to observe workers' performance and behaviour, social and cultural aspects of also need to be considered. Workers may resist the concept of remote surveillance and its use may erode trust between workers and management.

6. Conclusions

Many opportunities exist for the application of BIM to support health and safety management during the construction stage. Four key areas of practice on site have been proposed: hazard identification; scenario planning; communication and training; and monitoring and reporting. In all of these areas, the use of digital models and tools has the potential to improve not only the safety of workers but also the overall efficiency of the project. However, successful implementation of BIM in health and safety management requires proper planning, investment, training, and ongoing review and assessment.

Many tools and software are currently available, but they don't always interface easily with BIM or provide the functionality required in a Health and Safety context. In the examples presented in the literature, additional programming is often required to achieve useful applications. Because of this need for technical development, there is a risk of over-reliance on digital experts who are skilled in programming or modelling processes rather than on the safety experts whose knowledge and expertise are essential in developing relevant and accurate models and simulations in the safety arena. It is notable that throughout the literature, there is an emphasis that the tools are useful to support safety experts, and in no way replace them.

A key consideration throughout the discussion is the quality and extent of the BIM model. In each of these applications for health and safety, as in many other BIM applications, the most significant factor limiting the use of BIM is how thoroughly and consistently the model has been set up. The value of the BIM model is reduced considerably if the data input is incomplete or of poor quality. This includes the need to update and revise the model as changes occur through the life of the project.

Many of the examples of H&S applications detailed in the research require a level of detail within the model that is greater than is typically represented, to encompass temporary works, detailed connections between building elements, services etc. Similarly, the representations of transitional stages of the building within a 4D model required to fully manage the hazards as presented in a number of cases is also more detailed than would be commonly modelled. Relatedly, there is a shortage of skills in the area of 4D modelling, where practitioners are needed who are experienced in construction and understand the construction methodology, but also have skills in using the digital tools. Using less developed models would likely affect the types of hazards that could be identified or managed, but would not negate the benefits presented.

Many of the tools would benefit from development of knowledgebases at both an organisational level and a national level to capture experience and approaches to health and safety. At an organisational level, this would capture the experience and expertise of practitioners in terms of H&S practice, problems and mitigations so that lessons learned could be carried over from project to project. At a national level, databases of codes and standards are needed to allow consistent use of automated code checking throughout the design and construction process. A knowledgebase of accident types, frequency and severity would also provide useful data, so that appropriate emphasis can be placed on responding to the most significant issues.

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