Integrating
Building Information Modelling
and
Health and Safety
Design Phase

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January 2023

Project Partners:

Project Funding Partners:

Kindly supported by:

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Executive summary and Recommendations

Building Information Modelling (BIM) has an established role for health and safety (H&S) in the design stage. Safety in Design and Prevention through Design approaches can be adapted to the significant information which is available in a BIM model, which enhances the ability to practice these approaches. With the majority of NZ construction projects using BIM at some stage there is no reason that these common practices should not be supported with the design-level BIM model.

This report describes three technological advances which the international research and case studies show can have a significant impact on H&S at the design stage. These promising technologies: provide safety rule checks based on a BIM model; allow for formalised safety in design knowledgebases based on expertise from all in the industry; and support risk assessment from the design BIM model. While these technologies require significant investment, often at the national level to provide a complete solution, they identify simpler approaches that can be implemented by all in the design stage as highlighted in the recommendations below.

Recommendations

The review of the literature identifies that industry can benefit from BIM for Health and Safety in the design stages through a concentration on the following four areas:

- Provide 3D and 4D visualisations to allow all stakeholders in a project to interrogate the evolving design for health and safety issues. Here BIM provides strong approaches to collaboration on hazard mitigation across the project team as the design evolves and iterates towards construction. It provides methods to communicate and identify risks across a wide range of stakeholders in the project. Many tools are available in the marketplace to support these functions. Examples are BIM 360 and Navisworks.

- Use 4D BIM to analyse schedules to ensure safety measures are in place in a timely manner. Tools such as Navisworks support this process.

- Analyse the digital analogue of the designed building through the application of H&S requirements, knowledge banks and legislation to identify hazards and non-compliance. Tools such as Solibri Model Checker allow for rules to be defined, checked and visualised against a BIM model.

- Generate safety plans and evacuation plans automatically from the 4D BIM model. Tools such as BIM 360 Field allow for this functionality.

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List of abbreviations

3D	3 Dimensions
4D	4 Dimensions (3D plus time)
8D	Sometimes considered as BIM with safety information
AEC	Architectural Engineering and Construction
AIM	Asset Information Model
AIR	Asset Information Requirements
BIM	Building Information Modelling
CAFM	Computer Aided Facility Management
CDM	Construction Design and Management
CMMS	Computerised Maintenance Management System
COBie	Construction Operations Building information exchange
DfS	Design for Safety
EIR	Exchange Information Requirements
H&S	Health and Safety
HSE	Health and Safety Executive
HSWA	Health and Safety at Work Act 2015
IFC	Industry Foundation Classes
NZBC	New Zealand Building Code
OIR	Organisational Information Requirements
OSHA	Occupational Safety and Health Administration
PAS	Publicly Available Specification
PIM	Project Information Model
PIR	Project Information Requirements
PtD	Prevention through Design
SiD	Safety in Design

1. Introduction

This report is designed to inform the development of guidelines for building information modelling (BIM) and health and safety at the design phase. It uses practical lessons from international case studies and research. It offers directions for integrating BIM and health and safety – in the context of New Zealand's construction industry.

1.1. Process and structure

The starting point for this report was a systematic literature review by Guo et al. (2022) which identified 44 relevant international research articles and case studies related to BIM use for health and safety in the design stage and industry best practices. Each case study was considered based on its technicality, whether it could easily be implemented, and whether it was suitable for a New Zealand context.

The report is structured as follows:

- The introduction covers current occupational health and safety measures and applications, and highlights the need to integrate BIM into health and safety at the design phase. It further identifies the scope, source and trends used to achieve safety in design using BIM.
- The following three sections discuss three major technological approaches to attain safety in design using BIM.
- Finally, the conclusion summarises the findings of the report.

1.2. Construction health and safety

Worldwide, the construction industry has poor safety performance. Statistics show that 36% of all work-related deaths in Singapore are in construction. That number is 27% in the UK and 18% in the USA (Hossain et al, 2018).

According to Statistics New Zealand, the construction industry is the sector with the second-highest incidence of claims from 2009 to 2018, as shown in Figure 1. The industry has a high incidence of work-related claims in relation to most other industries, as shown in Figure 2.

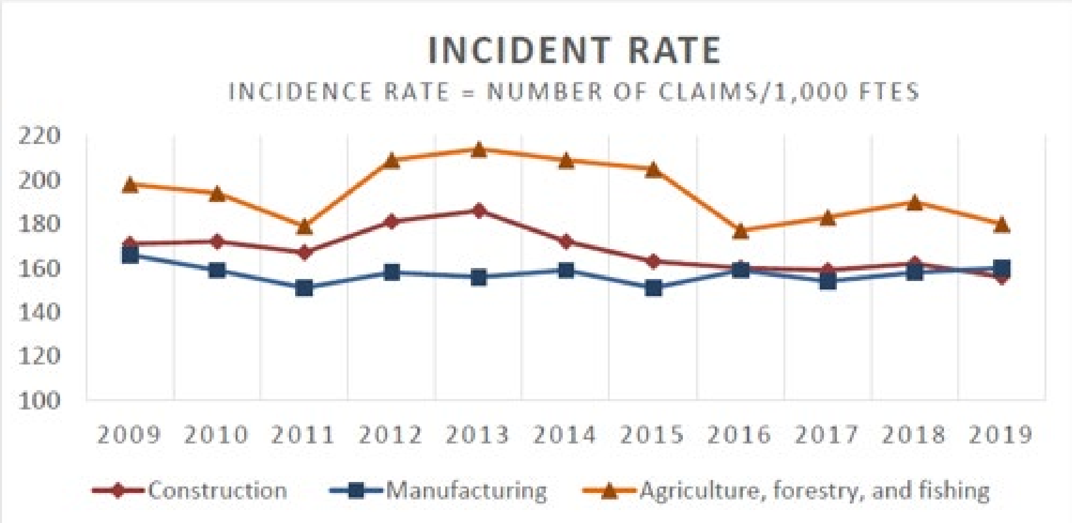

Figure 1: Incident rate of claims among sectors in New Zealand.
Adapted from StatsNZ (2020)

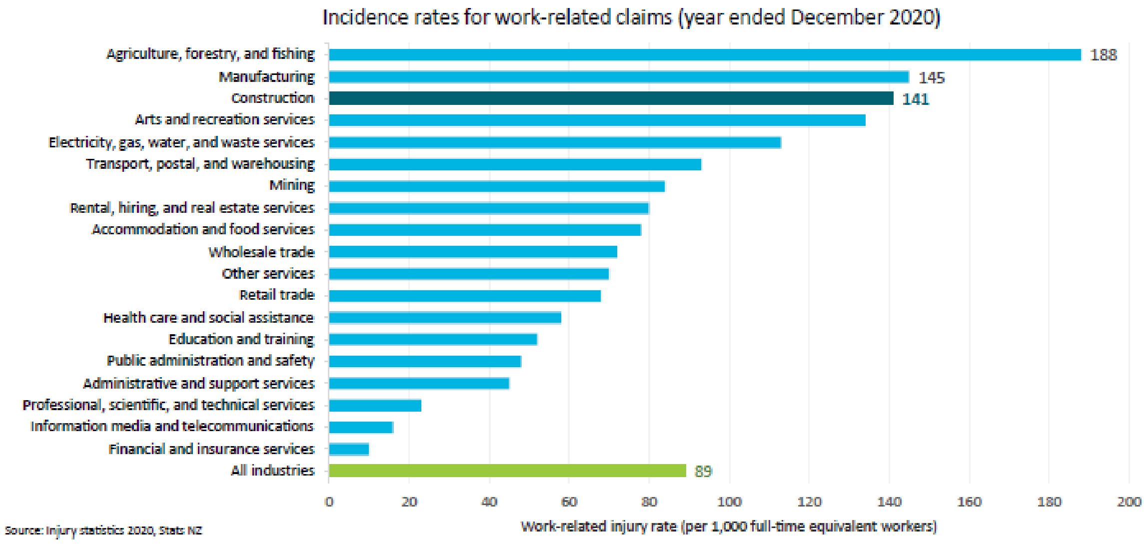

Figure 2: Incidence rates for work-related claims (MBIE 2021)

Riazi et al. (2020) identified that poor coordination between different disciplines contributes to poor health and safety outcomes in a construction project. BIM is a tool for coordination that can help improve the health and safety communication gap. The BIMsafe project provides lessons from case studies to encourage the industry to adopt the guidelines and use them. The project findings will improve the current risk prevention system through design in New Zealand.

1.3. Health and safety in design

Designers are in a good position to ensure that work is healthy and safe from the start. The concept of safety in design involves identifying hazards and assessing risks early in the design process.

Safety in design considers how to eliminate, substitute and minimise the risk of injury to people involved in constructing, operating, maintaining, decommissioning or demolishing an asset (Jin et al., 2019). It also considers the process of managing health and safety risks throughout the entire life cycle of buildings and infrastructure.

Health and safety is part of the concept of good design. Good design should use techniques that can minimise or 'design out' safety risks early in the design process to optimise employee health and safety through the project life cycle (WorkSafe, 2018).

Figure 3 shows that as a project advances through its life cycle, the ability to influence safety decreases and the cost of changes increases.

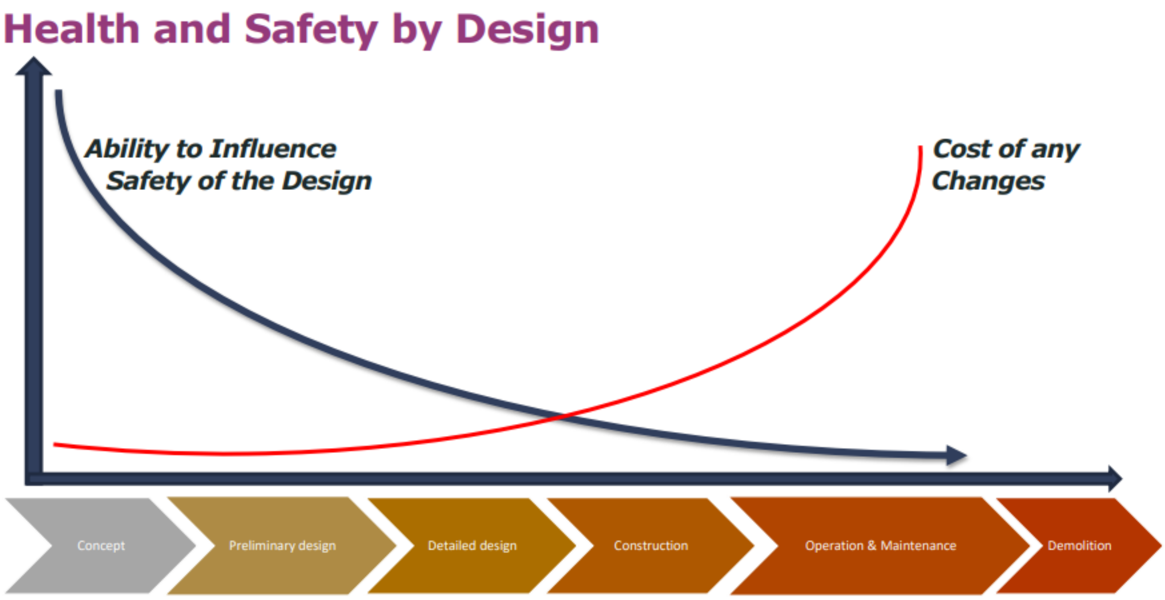

Figure 3: During the design phase, the ability to influence safety is at its highest while the cost of changes is at its lowest (WorkSafe, 2018)

Most safety risk mitigation in the construction industry aims to isolate, inform or control hazards. There is a huge opportunity to involve decision-makers in the early design stages and consider the full project life cycle. The earlier this process starts, the easier and more cost effective it is to make changes to better manage and eliminate hazards.

WorkSafe's (2018) report on safety in design outlines the hierarchy of controls and sets out a prioritised approach to managing hazards. The following subsection will discuss these.

1.4. Key principles of health and safety in design

This subsection discusses the fundamental principles for identifying and eliminating hazards. According to WorkSafe (2018), the key idea is that prevention is better than protection. Eliminating hazards is better than managing or controlling them. There are five fundamental principles, as detailed in Figure 4.

Figure 4: The five fundamental principles of health and safety in design (WorkSafe, 2018)

1.4.1. Risk management

Principle One: A risk management approach

Accidents happen when workers are exposed to hazards. Designers must reduce exposure to hazards as much as is reasonably practical (WorkSafe, 2018). When it is not practical to eliminate exposure, they should minimise it.

From an early concept stage, designers need to follow a systematic approach to identify and manage the work risks within their influence or control. WorkSafe (2018) documented the hierarchy of controls designers can use to guide their approach, shown in Figure 5.

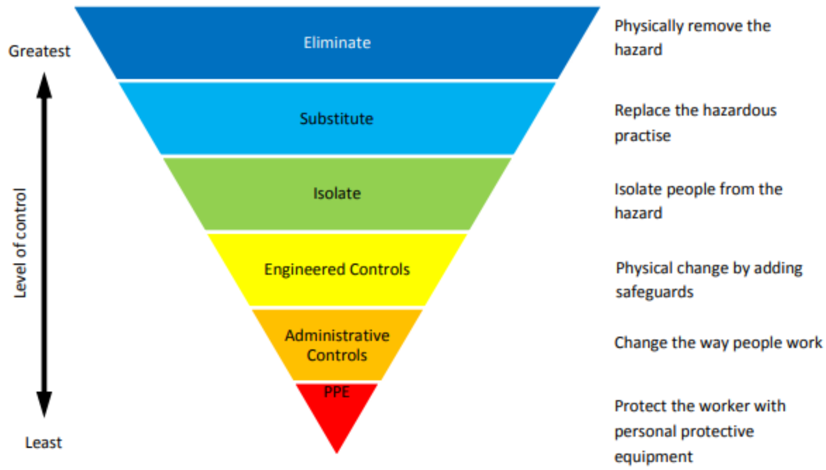

Figure 5: The hierarchy of control measures, from the highest level of control to the least (WorkSafe, 2018)

Principle Two: Life cycle

Health and safety by design is most effective when applied at the earliest stage, but designers should apply the principles of health and safety by design throughout a project's entire life cycle, from concept to decommissioning and disposal.

1.4.2. Quality management systems

Principle Three: Good communication and documentation

Good communication and documentation are essential for an effective health and safety management system. According to WorkSafe (2018), designers must give sufficient information to the people using the design. Designers need to create and provide documentation that includes:

- The identified health and safety risks
- How these risks were assessed in the design phase
- Proposed control measures
- All applicable standards
- The decision pathways taken throughout the design process

They must provide this information throughout the life cycle so workers know about any residual risks the designers could not 'design out', and how to minimise those risks.

One of the key tools for maintaining this information throughout a full building life cycle is building information modelling (BIM). BIM can also help the designer anticipate, visualise and foresee hazards and risks during the design phase (WorkSafe, 2018). BIM is discussed in later in the report.

Principle Four: Frequent monitoring and review

Monitoring and review ensures that plans are still fit for purpose as changes occur during a project. It gives a point at which continued relevance can be assessed and changes proposed to address variations. If there is any redesign required then the review can adapt control measures to suit. Monitoring and review also provides the opportunity to bring in the professionals who are impacted by the evolving design to be part of the decision making around H&S risks.

1.4.3. People

Principle Five: A capable team

Managing health and safety risks over the life of a building requires a capable team. Cooperation, coordination and good relationships between the designer and the client are essential. Construction stakeholders need to demonstrate a sound understanding of the project, technical knowledge, and strong leadership. People responsible for designing work processes and systems – such as health and safety professionals, safety, risk and reliability engineers and software designers – also play a key role in health and safety by design.

1.5. Building information modelling (BIM)

ISO 29481 (2016) defines BIM as a “shared digital representation of the physical and functional characteristics of a facility”. National BIM Standard (2013) states that “BIM is a shared knowledge of information about a facility. It forms a reliable basis for decisions during the lifecycle; defined as existing from earliest conception to demolition”.

BIM is becoming mainstream in the construction industry. A 2021 survey by EBOSS found that BIM use on projects has increased from 34% to 70%. The benefits of BIM include risk management (Bryde et al., 2013) and building information storage (Lu et al., 2021). BIM enables contractors to extract construction-specific information, which according to Zhang et al. (2015) is essential in supporting healthy and safe construction sites.

The ISO 19650 series indicates that BIM works best when better specifications are met with the right information during project design, construction, operation and maintenance (UK BIM Alliance, 2019). The ISO 19650 series’ definition of BIM shows that all stakeholders in a construction project, including clients, designers, contractors and subcontractors, are responsible for the overall process.

The next subsection discusses the ISO 19650 series in more detail.

1.5.1. ISO 19650 series

According to UK BIM Alliance (2019) the ISO 19650 series defines how information is managed across an asset’s life cycle. Ultimately, the standard is about good practices and asset management for the entire project team, across the entire life cycle.

- ISO 19650-1 describes the concepts and principles aligned to the project delivery phase
- ISO 19650-2 describes the delivery phase of assets
- ISO 19650-3 describes the operational phase of assets
- ISO 19650-4 describes information exchange
- ISO 19650-5 describes a security-minded approach to information management
- ISO 19650-6 describes health and safety

When applying ISO 19650 parties must tailor their information requirements to match the needs of their organisation, and each individual project.

Table 1: Definition of terminologies contained in ISO 19650 series
Adapted from UK BIM Alliance (2010), UK BIM Framework (2020), ISO 19650 (2018) and Building Innovation Partnership (2022)

Type of actors		Definition
1.	Appointing party	This is the organisation leading the project or asset management. It is usually the client, who may also be the asset owner for a project.

2.	Lead appointed party	This party is accountable for coordinating information exchange between task teams or between a delivery team and the appointing party – for example, the engineering consultant or general contractor.
3.	Appointed party	An appointed party is anyone generating information about the project – for example, a contractor, subcontractor, supplier, or consultant.
Type of teams		**Definition**
1.	Project team	The project team is any person involved in the project, regardless of appointment or contract arrangement.
2.	Delivery team	This is the lead appointed party and their associated task teams – for example, the contractor and its subcontractors and suppliers.
3.	Task team	A person or group performing a specific task – for example, the architecture team or a specific subcontractor.
Types of information requirements		
OIR	Organisations information requirements	OIR represent the key decisions and help prioritise information improvements. OIR defines why information is needed.
AIR	Asset information requirements	AIR represent the asset information products needed for key decision-making in the operation and maintenance (O&M) phase. AIR defines what information is delivered.
EIR	Exchange information requirements	EIR represent the asset information at each information milestone required for key decisions in the acquisition and O&M phases. EIR defines how information is delivered.
PIR	Project information requirements	PIR represent the asset information products required by key decision makers in the acquisition phase. PIR defines why information is needed.
PIM	Project information model	PIM is the delivered project information. It contains project geometry, equipment location, scheduling, construction methods, costing, installed systems details, components and equipment at the construction phase –for example, 5D BIM, COBie spreadsheet.

AIM	Asset information model	AIM is the delivered asset information. It is a single source of approved and validated information comprising models, documents, data and other information for the operational phase of a built asset—for example, COBIe spreadsheet, O&M manuals.

Guidance on information requirements and delivery is contained in section 5.0 of "*The Information Management* according to BS EN ISO 19650" (UK BIM Alliance, 2019). This document describes who does what, the information requirement hierarchy details, how responsibility is shared, and the collaborative method used to produce information.

Levels of information need in ISO 19650

ISO 19650-1 Clause 11.2 introduces the concept of 'levels of information need' and provides a method for determining the appropriate amount of information exchange required. In this method, the appointing party defines the information need according to the EIR and PIR (UK BIM Alliance, 2019). The appointing party records these levels of information need in Task Information Delivery Plans.

BIM related standards with respect to health and safety

UK BIM Alliance (2019) explains that in ISO 19650, Annex A, Table A.1, contains the summary of existing BIM standards developed to support BIM level 2. One of the standards specifies collaboration in the sharing of health and safety information using BIM, which is documented under PAS 1192 – 6:2018. At this time, ISO 19650 has adopted PAS 1192-6 for health and safety using BIM.

PAS adopted the five phases of the life cycle approach, as shown in Figure 6. The five phases show the progressive development of health and safety through a project life cycle.

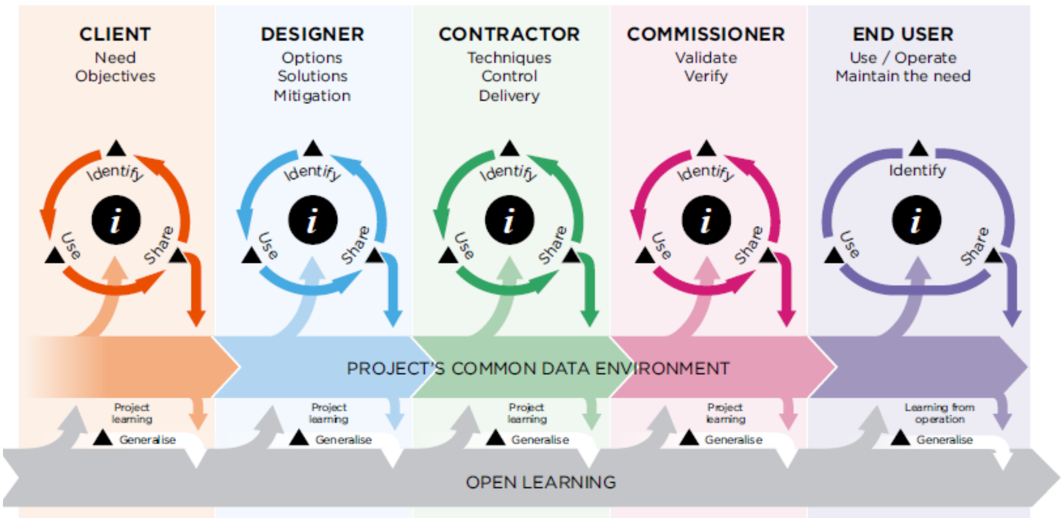

Figure 6: Progressive development of health and safety information according to PAS 1192-6:2018 (2018)

PAS 1192-6:2018 (2018) sets out the relevant clauses to adopt when using BIM to manage health and safety. For instance, it uses entities and annotation models to describe that project stakeholders must exchange and share risk information through an open standard structured form. The open standard is discussed in the next sub-section.

1.5.2. Open BIM standards

An open standard exchange concept enables parties to exchange information in a standardised way. Industry Foundation Classes (IFC) was developed by buildingSMART and is a standardised, digital description of the built environment and civil infrastructure.

IFC

IFC is a vendor-neutral and agnostic open international standard (Lees and Nisbet 2022). IFC can be used across a wide range of devices, interfaces and software platforms for many different projects (buildingSMART, 2022). The IFC approach shares information in a way that enables and encourages all parties to collaborate, and removes the need for re-entering data, custom import interfaces, or proprietary plug-ins. All parties can access the same data through all phases of the building life cycle, regardless of what software they use.

COBie

Construction-Operations Building information exchange (COBie), was developed in 2007. It enables designers and contractors to provide and update information about a project's operations, maintenance and asset management in real time. An international standard for building data exchange, COBie is used throughout the project life cycle. The use of COBie is helping to grow support for authoring tools, computer-aided facility management (CAFM) and computerised maintenance management systems (CMMS). COBie is a subset of IFC and is often represented in spreadsheets as in Figure 7 (ERDC 2021).

Column	Facility
Name	B005
CreatedBy	role@company.com
CreatedOn	2017-02-12T11:00:00
Category	En_20_15 : Administrative office entities
ProjectName	P005
SiteName	S005
LinearUnits	millimeters
AreaUnits	squaremeters
VolumeUnits	cubicmeters
CurrencyUnits	Pounds
AreaMeasurement	Indicative
ExtSystem	AEC3 BimServices
ExtObject	IfcProject
ExtIdentifier	1TB8MXxIf6BAI7EOFPDWY8
ExtSiteObject	IfcSite
ExtSiteIdentifier	1TB8MXxIf6BAI7EOFPDWYA
ExtFacilityObject	IfcBuilding
ExtFacilityIdentifier	1TB8MXxIf6BAI7EOFPDWY9
Description	Office building 5
ProjectDescription	Design and construction of new office building 5
SiteDescription	Site 5, North London Redevelopment
Phase	CIC 6 : Handover

Figure 7: COBie facility sheet (PAS 1192-6:2018)

Risk information representation using COBie

According to PAS 1192-6 (2018), *"risk should be documented in COBie issue sheet"*. This PAS recommends associating risks with two sources taken from component, zone, floor, system, type and job worksheets, as illustrated in Figure 8.

Column	Issue
Name	AAA12
CreatedBy	role@company.com
CreatedOn	2016-11-04T11:08:38
Type	Struck by falling object
Risk	Moderate
Chance	Low
Impact	High
SheetName1	Space
RowName1	Roof Terrace
SheetName2	Type
RowName2	Large feature planter
Description	Falling branches from height in heavy wind
Owner	role@company.com
Mitigation	Wind protection and ensure distance from edge
ExtSystem	
ExtObject	HS_Risk_UK
ExtIdentifier	

Figure 8: COBie issue sheet (PAS 1192-6:2018)

1.6. Risk information cycle

PAS 1192-6 (2018) identifies four key components to create a strong foundation for collaboration on health and safety information: identify, use, generalise and share.

Stakeholders are advised to apply these four components throughout the project lifecycle, across all stakeholders and between different interfaces.

The four components, shown in Figure 9, are discussed in detail in PAS 1192-6:5.2.3.4. PAS recommends directly and immediately applying lessons learnt, good practices and improved innovation, and sharing these to enable continuous learning.

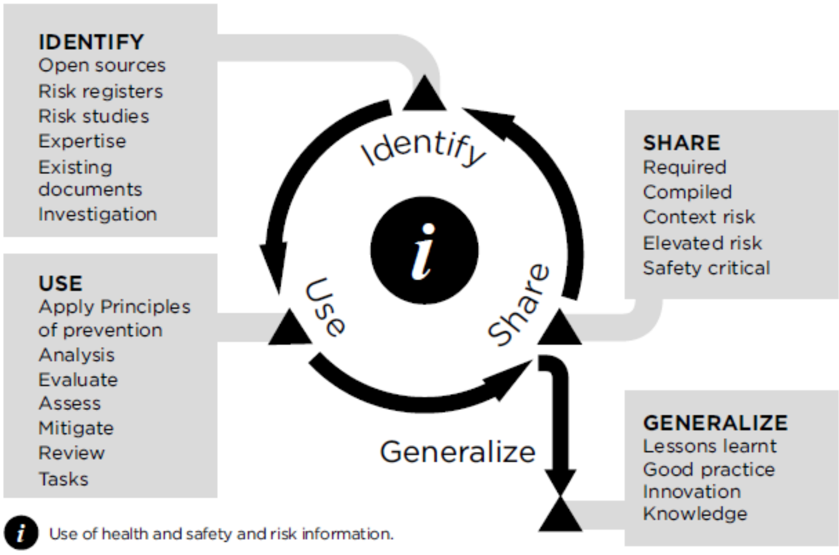

Figure 9: Risk information cycle (PAS 1192-6:2018)

1.7. Health and safety in design through BIM

Current academic research shows that BIM is a useful tool for improving health and safety outcomes throughout a project life cycle.

BIM allows parties to analyse occupational safety issues and help avoid hazards and risks (Guo et al., 2022). BIM models' virtual analysis and simulation tools help visualise and anticipate risks at all stages – design, construction and even end use. This allows users to modify designs and bring safety procedures into the model itself.

Designers can implement BIM models to accurately visualise and realistically sequence construction programmes for sites, structures and plants (WorkSafe, 2018). This puts designers in a better position to identify, anticipate and visualise hazard risks in the design phase.

Another important benefit of BIM is the concept of a 'single source of truth'. This concept has huge implications for construction health and safety and creates an opportunity to embed construction safety information into the BIM model. Users can intentionally design, evaluate and adapt each component of the health and safety 'file', and use it in real-time during a facility's conception, design, construction, use, and deconstruction. This process involves extensive collaboration with all stakeholders – all of whom can make informed decisions thanks to the single source of truth.

1.8. Sources and methods

A content analysis approach (Hsieh and Shannon, 2005) was used to select 13 papers out of the 44 articles identified through the systematic review. These 13 papers all have well-defined methodologies applied to case studies (Guo et al., 2022).

The sources of the papers were classified into four categories based on the area of study, as shown in Figure 10. This classification process revealed that four main factors contribute to achieving safety in design.

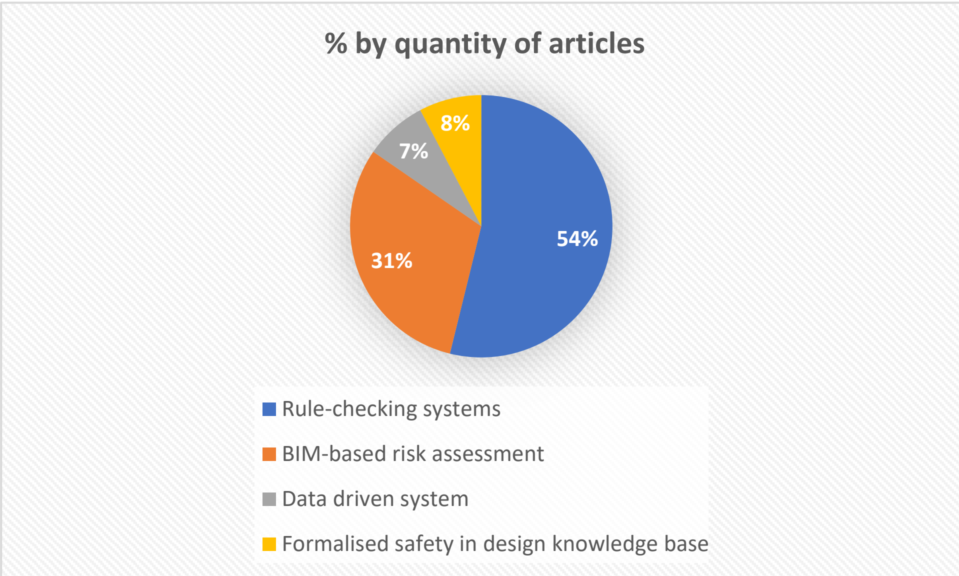

Figure 10: Classification of international studies on BIM-based systems for safety in design Adapted from Guo et al. (2022)

1.8.1. Rule-checking systems

Eastman et al., (2009) defined rule-checking as *"software that evaluates a BIM model against pre-developed rules to identify issues of interest and return reports"*. Automated safety rule-checking systems are created from construction schedules and three-dimensional designs. These systems detect clashes between different elements in the building systems. They also automatically identify embedded risks in the schedule as the building is constructed (Zhang et al., 2015). Applying rule-checking to identify hazards can save time compared to manual observation, which requires time to check, assess and identify hazards (Zhang et al., 2011).

The primary purpose of rule-checking systems is to flag hazards and recommend control measures. It does this by extracting relevant objects and attributes from a BIM model and generating reports based on computable safety rules. Many academic papers examined for this report show some limitations based on the maturity of the rule-checking system. For example, some safety rule-checking systems only work in certain contexts, while others can operate in different construction environments (Lu et al., 2021).

1.8.2. BIM-based risk assessment

Rule-checking systems do not identify the severity and consequence of risks, although some authors were able to quantify safety risks at some activity levels (Jin et al., 2019, Lu et al., 2021 and Lee and Choi, 2020). In these risk assessment approaches it is possible to quantify the likelihood and severity of a risk, and then after control measures are suggested it can determine the residual risk.

This method has challenges identifying hazards involved in the building design and its construction activity. Safety risks are developed as a product of likelihood, consequence and exposure. To mitigate the initial challenges of BIM-based risks assessment, designers can incorporate sequencing and scheduling into the BIM model.

1.8.3. Formalised safety in design knowledgebase

A formalised safety in design knowledgebase can form the basis of an improved rule-checking system. It enables enhanced problem-solving thanks to a knowledge-based library of safety rules. Users can check these against safety issues for any design element in the BIM model. These rules do not necessarily have to come from legislation, but can reflect the knowledge of experts in an organisation and the insights gained from previous projects.

According to Hossain et al. (2018) to consider just one hazard for safety checking would leave residual risks unidentified. Formalised safety knowledge can solve more problems when residual risks are properly documented in a risk register for further actions during the construction, operation and maintenance stages.

1.8.4. Data-driven system

This is the use of data mining and machine learning techniques on safety reports and BIM models, to enhance safety in design. For instance, Tixier et al. (2017) adopted an attribute-based approach that leverages textual safety-related attributes, such as building elements, to identify safety clashes. These safety clashes are the incompatibilities in the work environment known as ‘construction injuries’ – for example, confined workspaces and small particles. Designers can integrate a data-driven system with BIM by extracting attributes from a 4D model and visualising the safety clashes in BIM. The majority of benefits of this approach accrue in construction, so this will be covered in the next report in this series.

1.9. A note on terminology

There are several terms used to describe the concept of design for health and safety. North Americans call it prevention through design (PtD), Australians call it safe design, in Singapore it is referred to as design for safety (DfS) and in the UK it is known as construction design and management (CDM). These terms all refer to the same concept: that designers should use safe design to either 'design out' or minimise health and safety risks. The terms are used interchangeably in this report.

Safety in design (SiD) is the hazard identification and risk management of a project's lifecycle early in the design phase. The New Zealand Health and Safety at Work Act (HSWA), introduced in 2015, requires designers to eliminate or minimise health and safety risks for downstream stakeholders. This policy and regulation change is supported by evidence that SiD improves construction site safety (Behm, 2005).

2. Safety rule-checking systems

This section discusses the meaning of rule-checking systems, their development processes, and their application to health and safety during the design phase.

A rule-checking system evaluates the design information of the whole building model or building elements based on the relevant standards. For example, the New Zealand Building Code (D1 access routes) can be used to check safety of entry or exit from a building. Rule-checking systems help designers to identify, define and apply rules to conditions of importance in the model. Reports are returned to the designer which indicate 'pass' or 'fail' for each condition checked (Eastman, 2009).

2.1. The need for a safety rule-checking system

Rule checking during the planning and design phases helps eliminate hazards before they appear on a construction site.

The current approaches to safety planning typically involve paper-based check sheets or manual checks, which can lead to mistakes when producing reports for safety data and decision-making in construction (Ku and Mills, 2010).

Technology can play a central role in reducing incident rates and improving safety planning practices. For example, Gambatese et al. (2007) documented the benefits of a safety rule-checking system. These benefits included having a variety of approaches to project review, safety hazard identification, and suggestions for removing or reducing the chance of hazards. Another benefit is that technology can generate useable documentation, with design recommendations saved for future reference.

2.2. BIM-enabled rule checking

An advantage of BIM is that objects are modelled within the system and have information associated with them, such as the area or spacing between building objects. This information, attached to the objects, allows rule-checking.

For example, if a fire door is modelled as an object, information attached might include the fire rating of that door. An automated rule check can then confirm whether the door meets fire safety requirements, and which spaces the fire door is servicing. Object geometry can be automatically rule-checked. For example, the size of an opening in a slab can be checked to see whether a guardrail is required.

2.3. Rule-checking process

The rule-checking process is made up of five steps: rule interpretation, BIM model preparation, rule execution, rule checking report, and corrective actions. These steps are shown in Figure 11 and described in further detail below.

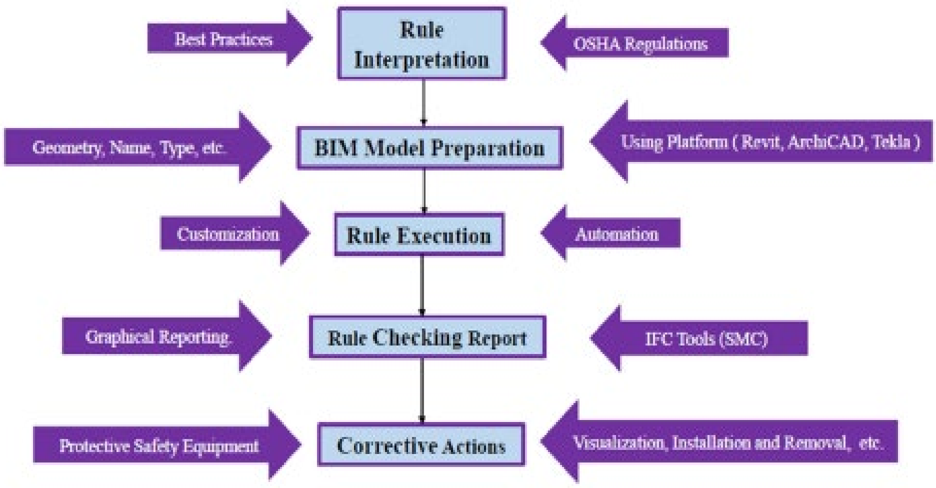

Figure 11: Steps in the rule checking process (Hossain and Ahmed, 2022)

2.3.1. Step One: Rule interpretation

Zhang et al. (2013) define rule interpretation as "a logic-based process of mapping rules from human language (natural language) to machine-readable format (parameterised rules)". In other words, rule interpretation translates written rules using an automated formula.

Two criteria are central to rule interpretation. The first criterion is the object where the rule applies – for example, a 'slab'. The second criterion is the property where the rule applies, or constraints between objects. For example, in the rule "no space containing a soil fixture shall open directly into a space used for the storage, preparation, sale or consumption of food" (NZBC-Clause G1, 2011), 'no space' is the constraint between the two building objects.

Another example of rule interpretation is shown in Table 2. In this example, a floor slab has an opening 'x', ranging from 5cm to 1m. When 'x' is less than 5cm, it does not require protection. When 'x' is greater than 5cm but less than 1m, it requires a cover panel. When 'x' is greater than 1m a guardrail system is required.

Table 2: An example of table-based rule translation for holes in concrete slabs (Zhang et al., 2011)

Length (x) of a Floor Opening in its Least Dimension	*Prevention Method*
< 5 cm	*"Not considered"*
5 cm < x < 1 m	*"Cover with panel"*
> 1 m	*"Apply a guardrail system"*

Interpreted rules can be stored in a system such as Solibri Model Checker or any other rule-checking system. According to Dimyadi and Amor (2022) rule interpretation is feasible in New Zealand. In their case study researching urban land development, planning regulations were translated and incorporated into the ACABIM commercial software system. However, they found that the cost and time of the human experts required for rule interpretation in New Zealand can be high.

2.3.2. Step Two: BIM model preparation

During preparation for the BIM model, it is important to ensure that BIM objects have been modelled with the correct level of detail (Getuli et al., 2017). Designers or drafters need to ensure that the required attributes from a rule-checking system are embedded within BIM objects and confirm that the values are accurate. These values may include the object geometry, relationships such as spacings between building objects, and building object material type (Zhang, 2013).

For example, Figure 12 shows a single window standard BIM object. The parameters of the window object are displayed in the pop-up template. A user can enter the attribute values, which can later be checked by a rule-checker. Additional attributes values required by a rule-checker can also be added.

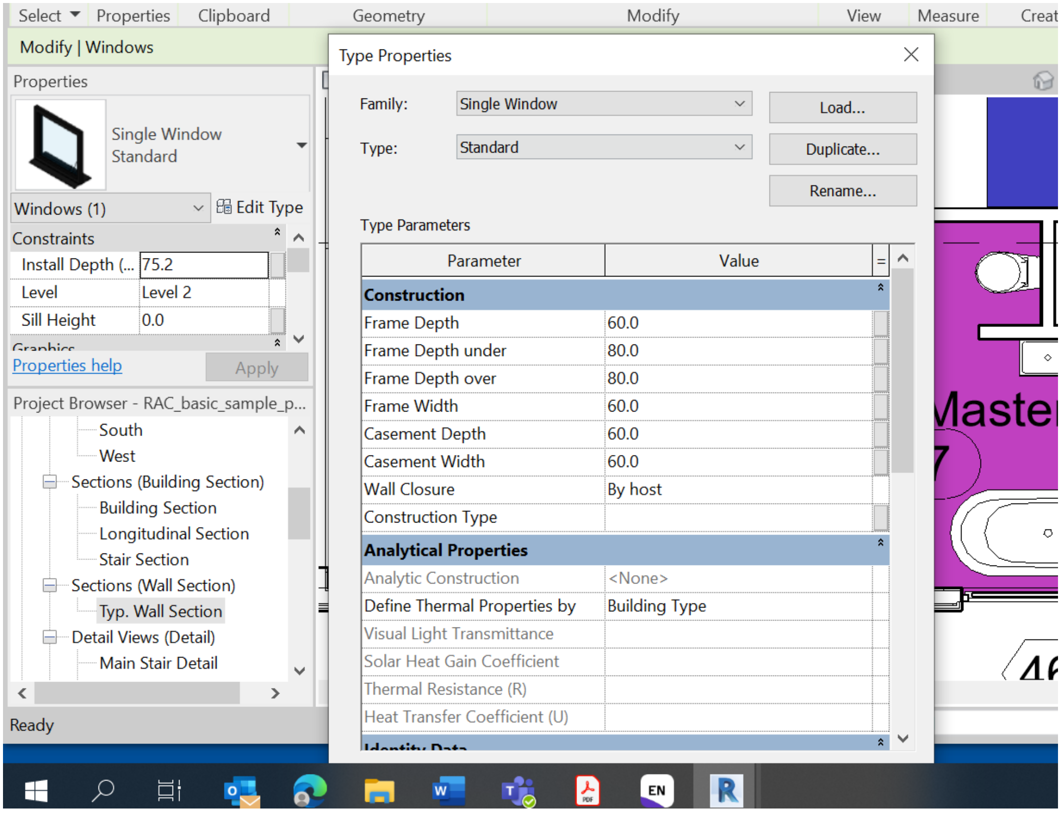

Figure 12: A typical window object in a BIM model with parametric values (Autodesk Revit, 2022)

During a building model audit at the time of building consent submission, a Building Consent Auditor can check values added by designers or drafters, making this step practicably achievable in a New Zealand context.

2.3.3. Step Three: Rule execution

At the rule execution phase, the geometric and attribute data of the BIM objects and the relationships between building objects can be checked against the applicable code clauses (Getuli et al., 2017). A typical example is demonstrated in Figure 13, in which a written rule regarding the safety distance of objects has been violated when the safety rule-checking has been applied.

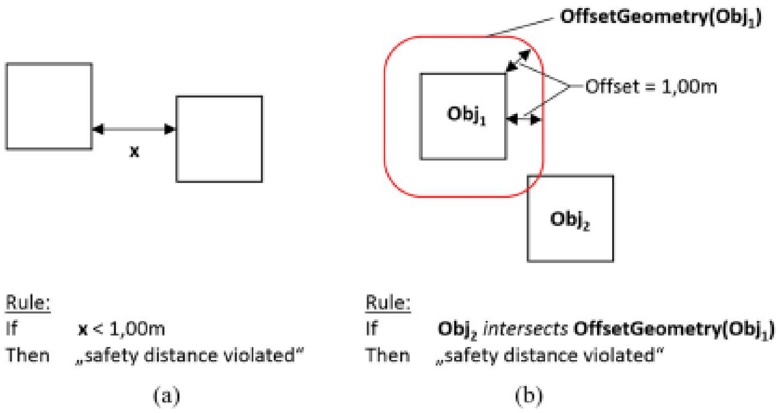

Figure 13: Safety distance between objects in 2D: (a) distances between edges; (b) intersection of offset geometry (Hossain and Ahmed, 2022)

Rule execution is designed to have two steps. First, to "automatically check the model and apply safety measures according to default settings of a model checker" and second, to "provide all possible solutions that can be selected from the model checker based on individual experience and best practices" (Zhang et al., 2013)

The rule execution approach can be directly applied in the New Zealand industry if the cost and time for rule interpretation can be addressed. Dimyadi et al. (2016) provide similar cases where audit engines were used to check a given design represented in a Building Compliance Model (BCM).

2.3.4. Step Four: Rule-check reporting

This is the report generated after a rule execution has been applied to a building model. A safety-check report can come in two forms, a 3D visualisation of failed elements or a table-based report of rule conflicts.

Figure 14 shows a 3D visualisation with failed building elements highlighted in red and suggested guardrail protection for the slab edges in yellow. Figure 15 shows a table-based report listing rule conflicts and suggestions. It also includes a rule checker interface showing parametrised rules. Figure 16 shows a tabular report from the ACABIM system.

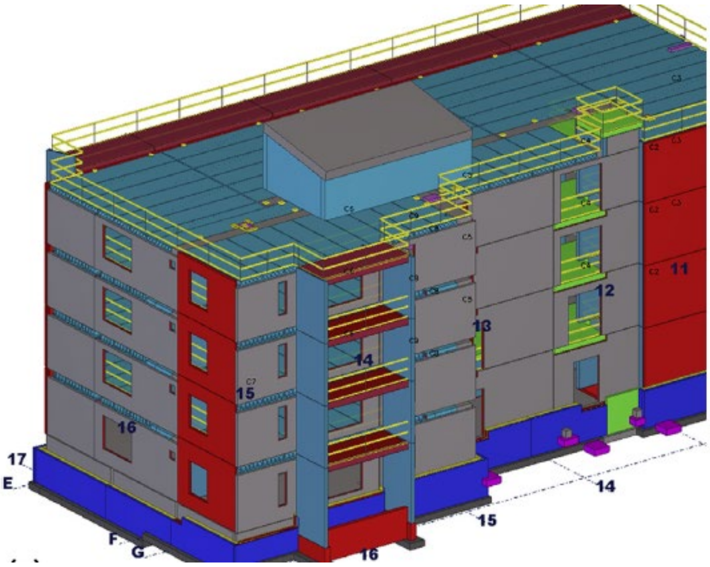

Figure 14: A 3D visualisation showing failed wall openings and suggested guardrail protection (Zhang et al., 2015)

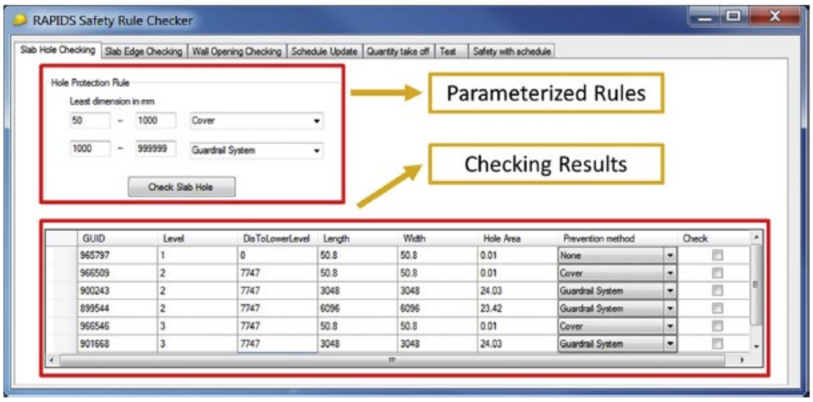

Figure 15: A table-based report for slab hole user interfaces (Zhang et al., 2015)

CAP Library	Fire Safety
Audit Name	Fire_Severity_Calculations
Critical Building Storey	1
Critical Space Name	103 Office
Enclosure Fire Rating	30 min
Vertical Opening Area	2.17 sqm
Effective Opening Height	1.2 m
Max HRR	1577.48 kW
Calc. Message	Space [0DFiCEmcH7YPktRl38gME5] has potential peak HRR exceeding threshold
Audit Outcome	Enclosure Fire Rating NOT adequate

CAP Library	Accessibility
Audit Name	Check_Vertical_Transportation_Requirement
Building Storeys	3
Lift Provided	1
Audit Outcome	Lift is NOT required. OK.

CAP Library	Accessibility
Audit Name	Minimum escape routes
Critical Building Storey	2
Critical Space	217 Corridor
Critical width	950 mm
Audit Outcome	Width below prescribed threshold of 1000 mm

Figure 16: A safety check performed for fire safety and accessibility in a three-storey building (ACABIM: https://cas.net.nz/)

2.3.5. Step Five: Corrective actions

A safety correction is the action taken when a hazard is identified at the design phase. If the rule-checking report from previous steps reveals any rule conflicts, the designer may revise the design to correct this. Another possible action is incorporating prevention methods, such as guardrails or slab covers. The prevention method can be visualised in a 3D environment, as was seen in Figure 14. This visualisation enables quick decisions to be made and increases safety awareness among project participants.

2.4. Defining the rule source

This section discusses the source of safety rules for model checking systems.

2.4.1. Codes and standards (and their limitations)

One approach to safety checks started in 1997 when Hinze and Gambatese (1997) constructed a toolbox with 430 safety in design suggestions from building regulations. Marini (2007) added more than 100 safety in design suggestions to the toolbox in 2007. These authors constructed their safety toolboxes by collecting safety rule suggestions from design manuals, ideas from researchers and interviews with industry experts. In later years, additional researchers further improved the toolboxes by adding suggested rules from the UK health and safety regulation (HSE) and Occupational Safety and Hazard (OSHA) regulations (Zhang et al., 2015 and Qi et al., 2014).

A typical example is a rule-checking system by Zhang et al. for fall prevention and slab opening. The system consists of BIM software (Tekla) and a Solibri Model checker to achieve an engineering control safety level (Jin, 2019). The limitation of this system is that the Solibri model checker may not contain all the required parameterised rules for some specific safety checks, so extra effort may be required to interpret new regulations for some rule executions.

Some design and consulting companies are already using BIM integration in New Zealand – for example the ACABIM compliance platform that can handle standard integration for efficiency and safety (Dimyadi et al., 2016). There is an opportunity to adopt Zhang's safety-checking system and to improve the model by applying further rule interpretations (using New Zealand rules). Barriers to this opportunity include the time, effort and cost of interpreting rules, and the need for a subscription to Solibri .

2.4.2. Constraints and limitations

Rule definition

Rules are usually written in natural language, and should be precise and easy to understand.

Rules that specify certain geometric and connectivity restrictions between building objects can be interpreted for use by machines, but this process requires significant effort (Solihin and Eastman, 2014). Expert knowledge is required to interpret the meaning of rules because some rules can be ambiguous or complex.

Eastman (2009) applied a logic-based interpretation method which confirmed the importance of transforming complex rules into simpler rules that are precise and easy to understand. In their approach, transforming complex rules to simple rules was done by asking a series of questions. During the interpretation process, assumptions can be used to help to understand the rule-checking requirements.

Rule interpretation is already in use in New Zealand. An example is the interpretation of New Zealand building codes by building consent authorities (BCA) in the form of checklists developed for consenting (Auckland Council, 2019).

Table 3 helps to illustrate the complexities involved in rule interpretation, and how much implicit knowledge is required in the process.

Table 3: Questions that arose during rule interpretation (Solihin and Eastman, 2015)

Clause reference	Description	Questions during the interpretation process
Reg. 44(1) BCA	Protection of staircase and staircase landing	1. What are the criteria for when the protection starts to be required? What is the height of the protection? How about the shape of the protection (especially when there are gaps)?

Clause reference	Description	Questions during the interpretation process
	Every staircase or staircase landing shall be protected on any side overlooking an air-well, courtyard, void or external open space by either a railing, parapet or balustrade capable of resisting the lateral loading as specified in Table 4 of the Fourth Schedule.	2. What exactly is defined as 'overlooking'? Is a full glass wall considered 'overlooking' and therefore requires additional protection, or can the glass wall be considered a protection? 3. How far can a protection, e.g. railing, be from the edge before it is no longer considered a protection to that edge? 4. If the edge has a gap to the adjacent edge, how large a gap is allowed before protection is needed?

2.4.3. Best practices

Safety in design best practices are the most effective safety measures for preventing occupational health hazards. Zhang et al. (2011) proposed several safety in design suggestions collected from HSE and OSHA regulations, classified into five categories: falls, struck by, caught in/between, electrical shock, and other. These are shown in Figure 17.

Each hazard category can be further organised – for example, falls. According to Huang and Hinze (2003), 40% of all construction worker deaths result from fall hazards. 40% of fall deaths result from roof and floor edges and openings (Coates 2011). Zhang et al. (2012) organised OSHA fall protection regulations into three components: definition, general requirements and prevention criteria. The definition details the unsafe area, the general requirement details the protection method used in a specific scenario, and the preventive criteria details the information required for the prevention system. Figure 17 shows the organisation of the fall hazard category into locations where these occur.

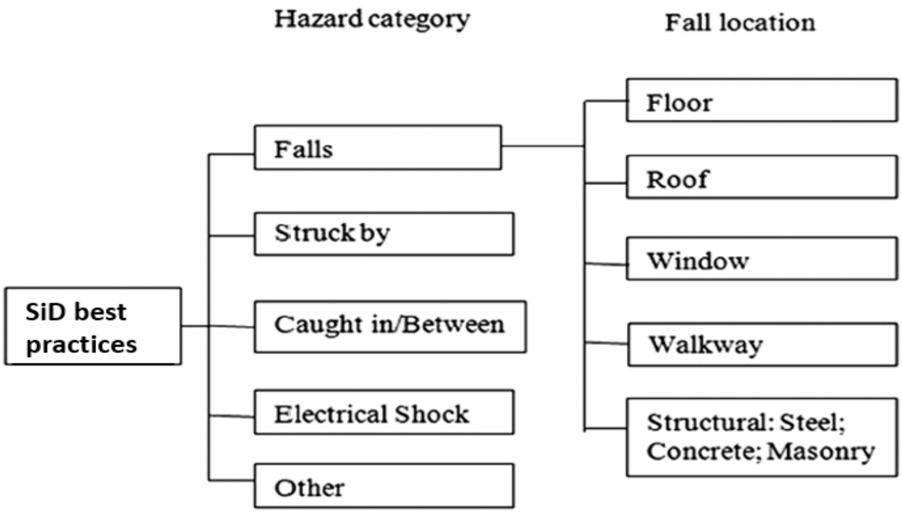

Figure 17: Classification of safety in design best practices, adapted from Zhang et al. (2011)

Safety in design best practices form the basis for further research into health and safety during the design phase. For example, Zhang et al. (2013) investigated the practical application of safety in design during the design phase for identifying holes in the slab and potential falls from a height, when the conditions set by hard-coded rules in the Solibri model checker are not met.

2.5. Case study

The case study aims to demonstrate the practical application of the health and safety checking tools identified in the literature, their limitations, and the lessons to learn from them. Overall, a typical case has been identified with the safety tool adapted from Zhang et al. (2013). The tools used in the case study have been adopted and applied using two different safety design rules for safety rule-checking. It could potentially be used to investigate applicability for the New Zealand construction industry.

Introduction

This case study examined the effectiveness of the safety rule-checking platform on a high-rise building project.

While the standards and rules for protective safety equipment vary by country, a growing number of international companies and industries are in need of tools that can allow all-round understanding and planning of safety at the design phase, regardless of the country in which they operate.

Scope

In this case study, the authors applied their tools (Tekla and Solibri model checker) to detect potential fall hazards which includes openings in the slab and slab edges that were unsafe and to recommend safety measures such as a “cover” and a “guardrail system” respectively. The safety report provided the visualisation of the fall protection equipment in BIM, and the developed rule-checking system automatically generated quantity take-off and installation and removal schedule information for the guardrail system and hole covers.

Building details

The case study is a building information model representing an 87 m tall reinforced concrete building with a gross floor area of about 75,000 m^2. There is an object-based 3D building model of a high-rise building. The building model has different openings on the slabs and the rectangular slab edges, including polygonal slab edges. The model was exported to the IFC open representation (Zhang et al. 2015). Then the safety rule-checker system is applied to identify fall hazards and their mitigation plan.

Applied rules

Two of the most common fall protection methods have been considered for rule-based checking (Zhang et al. 2015): cover for holes and guardrail system. According to OSHA 1926.502(i), “covers shall support at least twice the maximum load of the largest traffic load”. According to German safety rules, “the top rails must be located at the height of 1.00 m plus/minus 0.05 m". The US equivalent rule states that "the height of the top rails must be 1.10 m plus/minus 0.08 m above the working level”. Three rules were used to detect the geometry of fall hazards in the practical case study, however, two of the rules have been interpreted as shown in Table 4 and Table 5.

Table 4: Rule interpretation for a hole in a slab (Zhang et al. 2013)

OSHA rule		German rule	
< 0.05 m	No action required*		
0.05 m < x < 1 m	Apply cover	< 3 m	Apply cover
Otherwise	Apply guardrail system	Otherwise	Apply guardrail system

Table 5: Rule interpretation for a hole in an exterior wall (Zhang et al. 2015)

OSHA rule		German rule	
Drop height < 1.8 m	No action required*	Drop height < 1 m	No action required*
Drop height > 1.8 m	Apply guardrail system	Drop height > 1 m	Apply guardrail system

A fall protection safety rule-checking system is developed as a plug-in to BIM software. This system can check the geometric attributes directly in an Industry Foundation Classes (IFC)-based BIM

Figure 18 shows the safety parameters for the guardrail protective system showing two different provisions from each regulation for providing a guardrail protective system.

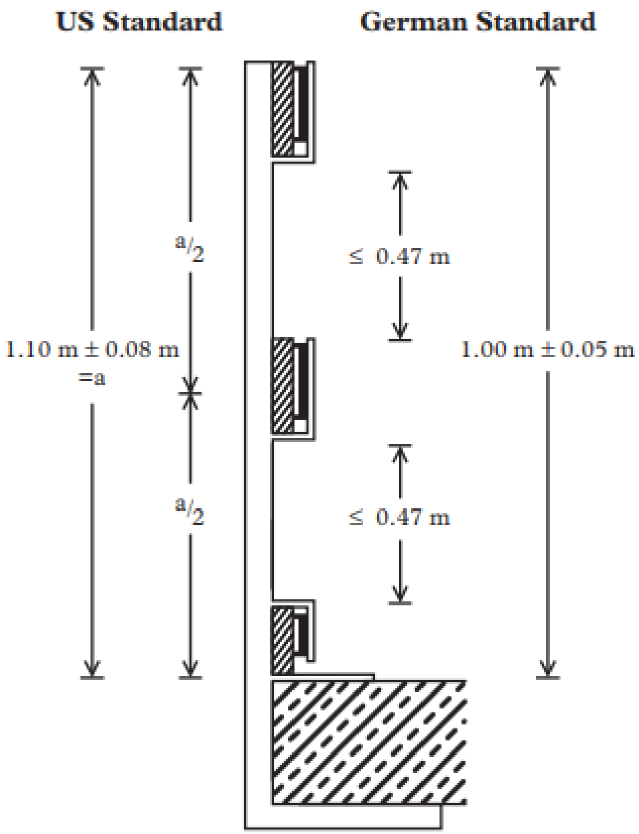

Figure 18: Safety parameters applied according to the two different regulations (Zhang et al. 2015)

Results and lessons

This sub-section discusses the result of the application of the safety rule-checking system and compares the result for the application of different safety regulations such as the OSHA and the German safety regulations and their lessons (Zhang et al. 2015).

1. Estimating, managing, and controlling change orders in design and construction planning processes:

The current traditional way of applying health and safety during the design phase can result in frequently occurring change orders, leading to a revision of drawings and requiring re-design, cost, and schedule adjustments. However, the developed technology can improve the existing processes in at least three ways:

(1) based on the design model, the safety engineer applies the rule-checking system and makes necessary design modifications after visualising the potential hazards;

(2) the bill of quantities is generated automatically; and

(3) the generated report can support the foreperson in ordering the correct type and amount of safety equipment delivered just in time.

2. Time savings

The authors indicated that the BIM-based safety planning and design delivered detailed reports and visuals in a few minutes. Compared to manual observation and drawing reviews that require large amounts of time, are labour-intensive, and consequently cost more money than planned for safety with human-assisted tools.

3. Quantity take-off of safety equipment

The quantity take-off for the automated safety rule-checking system identifies where, when, what, and how much equipment is required for fall protection. For example, Figure 19 shows the results of the safety rule-checker with detected hazards and automatically applied guardrail systems and covers for the holes and leading edges. With the applied safety rule-checking system, safety engineers can detect and assess safety hazards and finally evaluate the most appropriate and cost-efficient safety method using quantity take-off of safety equipment, as shown in Table 6

Table 6: Quantity take-off for guardrail system for the seventh floor (Zhang et al. 2015)

Floor No. 7	Length: 157.89 m	
Quantity	Type	Dimension
79 pieces	Post (steel)	100 cm
316 m	Railbord (wood)	3 cm × 15 cm × 200 cm
158 m	Toeboard (wood)	3 cm × 10 cm × 200 cm

4. Visualisation of results

The virtual environment can help to improve occupational safety education and training efforts. The objects of the building model can provide realistic visuals of the construction environment and function as valuable aids in the safety decision-making process during the design phase.

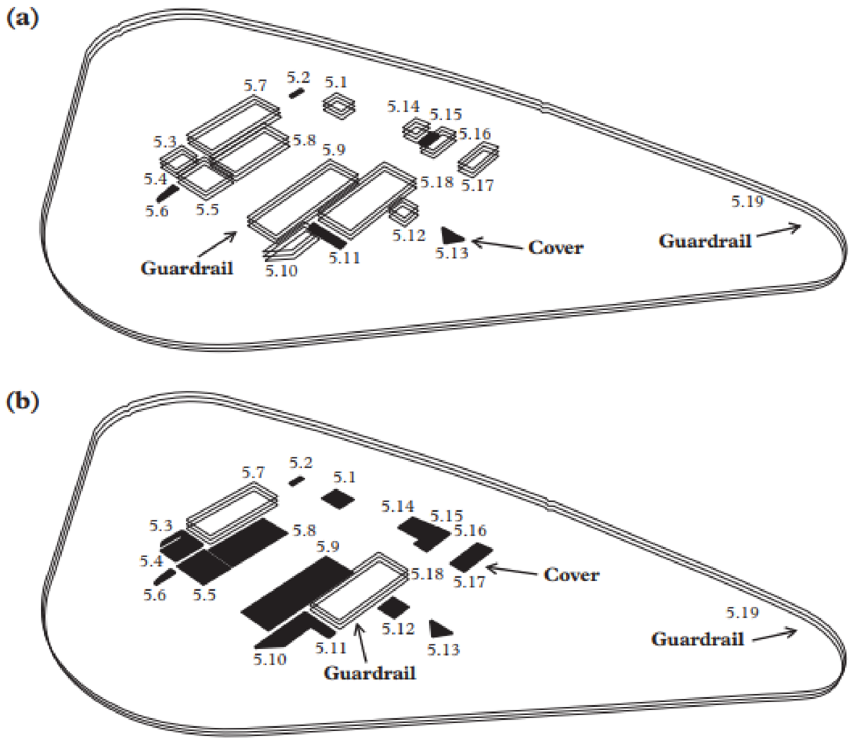

Figure 19: Protective safety systems (guardrail systems and covers) proposed by the safety rule-checker for edges and holes based on (a) OSHA guidelines and (b) German safety standards (Zhang et al. 2015)

With this information, engineers can explain to work crews where hazards exist and how appropriate safety equipment can be installed or what it should look like in the field.

5. Unprotected edges and holes in the slab

In this case study, the safety rule-checker reporting system generated a report for preventive equipment, which identified the need for guardrails of about 157.89 m for several unprotected slabs in the building (Zhang et al. 2015). With this report, safety personnel can estimate the exact amount of materials for the guardrail protection provision. The rule-checker detects the holes on the slab, and prevention methods can be suggested. The extraction of the report results from identifying all the slab openings found on the fifth floor is detailed in Table 7.

Floor no.		Floor area		Area of all openings	
5		1369.85 m^2		121.98 m^2	
Hole no.[Floor.Hole]	Area(m^2)	Width(m)	Length(m)	US standard	German standard
5.1	3.46	2.16	1.60	Guardrail system	Cover
5.2	0.55	1.42	0.39	Cover	Cover
5.3	1.20	1.96	0.62	Cover	Cover
5.4	3.91	2.06	1.90	Guardrail system	Cover
5.5	8.16	3.25	2.51	Guardrail system	Cover
5.6	0.92	1.79	0.52	Cover	Cover
5.7	21.32	6.88	3.10	Guardrail system	Guardrail system
...	...	...	...	...	...

Table 7: Extraction of the fall detection report for holes in the slab found on level 5 of the building (Zhang et al. 2015)

Limitations

Even though the automated safety rule-checking proposed by Zhang et al., (2013) can improve project workflow and safety quality, it has some limitations. For instance, during the rule interpretation of applied safety regulations such as the OSHA or German standard, it took much effort to analyse and convert text-based safety regulations into a table-based machine-readable format (Zhang et al. 2015). It also takes a lot of time when done manually. It becomes a challenge if a future change in safety regulations occurs, with a complex process to convert it into a machine-readable format for rule execution.

The changes that often occur during the design phase affect the geometry of the whole building or building elements. So, these modifications can affect the outcome of the safety rule-checking system. The safety or planning engineer needs to restart the safety rule system whenever the model, objects or attributes are changed.

A BIM model of a building that does not account for the construction sequence can pose a disadvantage to the safety rule-checker system. For example, buildings can be erected in many different construction stages, e.g. concrete pours require joints between them. So, if the process is not sequenced, hazards could occur in between, and the safety rule-checker system will not pick this up.

Safety rule-checking in BIM, whether automated, human-assisted, or manual, may find its greatest limitation when accounting for workers, e.g., safety behaviour.

2.6. Summary

Automated rule checking should be developed for use in NZ. As a system checking for a range of specific H&S risks during design it is within the reach of most large practices and could be developed as a service to sit alongside major BIM tools used in NZ. The software required to undertake rule-based checks of BIM models (and visualisation of outcomes) is widely available (e.g., Solibri Model Checker), but needs to have libraries of NZ H&S checks developed to be applied to a BIM model. This interpretation and coding of the NZ legislation is a highly technical job and needs a rigorous QA process to ensure that provisions are accurately interpreted. The libraries also need to be well maintained as codes and standards are updated frequently.

Once implemented the automated checks are quick and accurate, and can provide expert judgement for remedies to issues which are identified. As seen in the case study, only a small number of checks were implemented, and it is likely that initial offerings in the NZ market would not provide full coverage of all H&S checks, in order to keep the development time and cost reasonable.

3. Formalised safety in design knowledgebase

A formalised safety in design knowledgebase allows for the systematic description of risks associated with particular elements or building systems alongside the mitigations that could resolve these risks. These collated risks are then able to be accessed in design environments (e.g., BIM tools) to help designers who may not be highly trained in safety standards and the associated best practice for risk mitigation. While there are similarities, they differ from rule-checking systems by capturing a knowledgebase of potential risks and mitigations rather than rules to check against legislative requirements for a building. As such they are likely to be less subject to the frequent changes required to keep up to date with evolving codes and standards and incorporate more knowledge of issues and approaches from industry experience.

Research projects such as Hossain et al. (2018) identify a framework that is required to implement a formalised safety in design knowledgebase. The core of such a system is a library of hazards and mitigations. Hossain et al. (2018) specified a rigid structure to capture knowledge of hazards and their mitigations (see Figure 20).

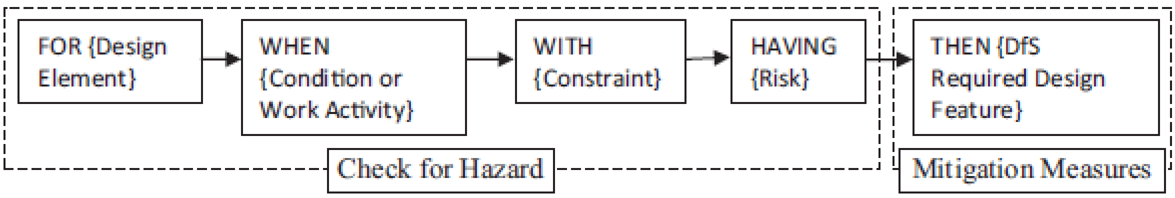

Figure 20: Structure of hazards and mitigations (Hossain et al. 2018)

With a library structure defined the library has to be filled with the agreed set of hazards and mitigations. Hossain et al. (2018) describe utilising focus groups to collect the expert knowledge and to reach agreement on how it is described and mitigated. They collected several hundred safety rules into the library classified and organised around the elements found in the IFC open BIM standard. Recognising the commonality between approaches for different elements they defined tables to independently capture a range of aspects of the described risk that could be reused across the project. This included tables for work activities in different parts of the project; risk narratives that could be applied to an element or building system, and mitigation narratives that could be applied to a risk.

With the risks modelled a reasoning engine can be used to associate particular risks from the library with the elements in a design and to provide advice to a designer around a particular designed element or building system. Figure 21 shows such a system in use. Hossain et al. (2018) identified that not all risks notified by their system would be resolved at the design stage, and that many risks would be addressed during construction.

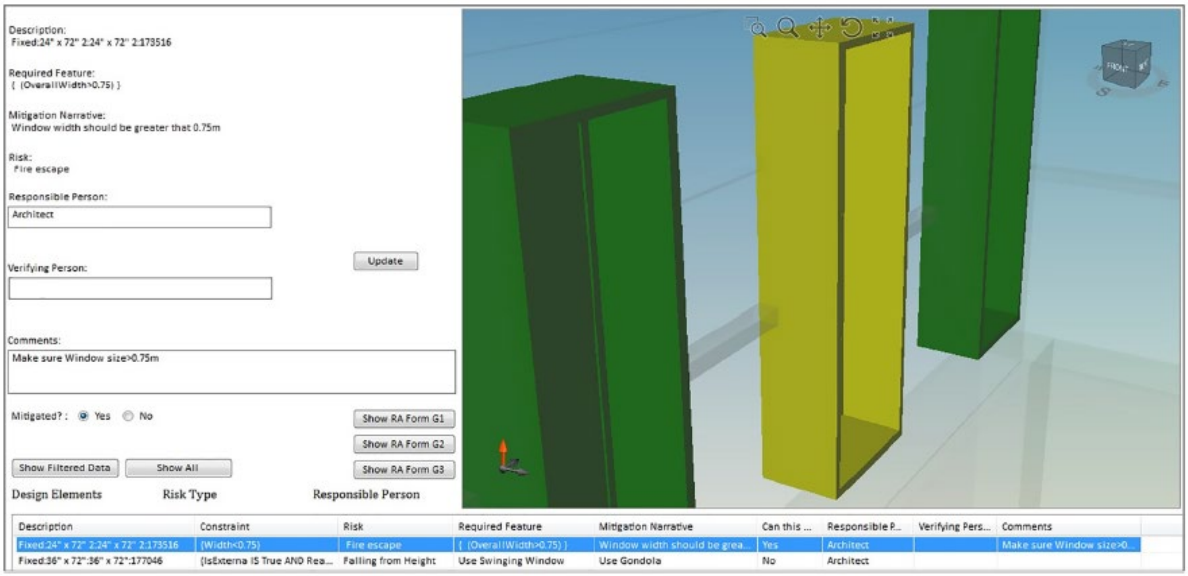

Figure 21: Example of risk identification and mitigation for building elements (Hossain et al. 2018)

3.1. Summary

A formalised safety in design knowledgebase covering the full spectrum of elements and building systems would be a major undertaking even for the largest of companies in New Zealand and even for industry bodies and government. Finding a way to collate the expert knowledge from experienced practitioners, to validate the identification of elements and building systems, and to agree on correct mitigations would be a mammoth piece of work. At this point in time such a system is not seen as feasible for New Zealand. However, if other nations decide to develop such a knowledgebase then New Zealand should aim to align with their efforts. What would be recommended in the New Zealand context is to utilise knowledge management systems within companies and professional bodies to collect and disseminate the expert knowledge of approaches to mitigate safety hazards.

4. Risk assessment in BIM

Risk assessment in BIM provides a way to address a limitation identified in the formalised safety in design knowledgebase approaches, that the actual risk in a project is not able to be quantified. When incorporated in a software tool attached to BIM then it should also reduce the variability of quality in risk assessment which could come from different experience levels in those undertaking the reviews (Lee et al. 2020). It is also proposed that this approach is less likely to impact on designer freedom during design, as it is typically applied in an iterative fashion after design milestones are reached (Jin et al. 2019).

To achieve the quantification of risk in a project there are several inputs that need to be sourced and data availability conditions to be met. Of core importance is having sufficiently detailed information about accidents in the construction industry, their severity and frequency, so that the risk of a particular activity and the associated building elements can be determined for the industry. In research in this area it has been identified that this can be difficult to source. Jin et al. (2019) identify databases in the USA which provide this information, but Lu et al. (2021) have no similar detailed data for China so need to use the USA data for their framework. Without this data for a particular nation it is clear that the calculated risks for construction and building elements will be inaccurate as they don’t reflect the industry’s performance and issues. The risk assessment approaches also need to have a time-base and work breakdown structure associated with the BIM model (Jin et al. 2019; Lee et al. 2020), creating a 4D BIM model, so that the impact of different activities and professionals on the site can be determined and visualised. The research in this area proposes that they are able to address higher levels in the hierarchy of controls (e.g., elimination of risks and substitution) as the risk assessment is applied through a prevention through design (PtD) process.

When linking the risk score of a design element (as calculated from national accident databases) to BIM it is then possible to calculate the risk of each individual element (e.g., by the size of the element) as well as the risk for all elements of a particular type (e.g., by summing the risk for each element) and for the project as a whole. See Figure 22 for an example from Jin et al. (2019).

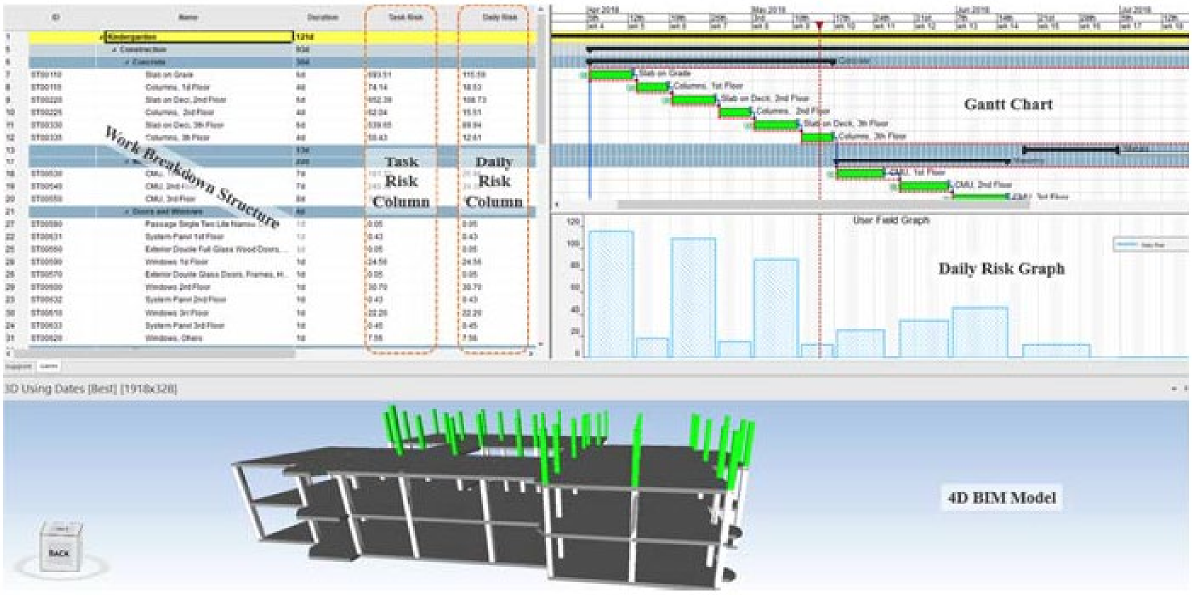

Figure 22: Example of risk assessment in Synchro PRO (Jin et al. 2019)

When the work breakdown structure is input to create a 4D BIM then the risks of particular activities which are associated with a building element can also be determined to calculate and visualise the risk profile of the project over the planned construction period (see Figure 23).

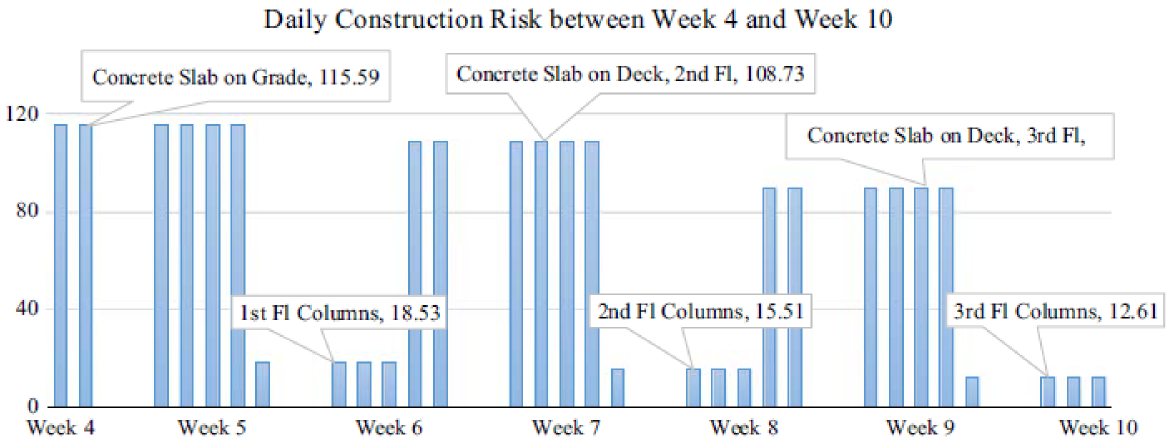

Figure 23: Example of risk assessment viewed by week of construction (Jin et al. 2019)

While the visualisations developed by researchers for risk assessment in BIM provide significant insight to risks and help designers focus on areas to design out hazards they can also be supported by risk control measures. Lee et al. (2020) show that for each hazard a range of control measures can be suggested, and depending upon what is chosen the risk likelihood calculation is recalculated to show the impact of the measure.

4.1. Summary

A risk assessment system for BIM covering the full spectrum of elements and building systems would (as for the formalised safety in design knowledgebase) be a major undertaking even for the largest of companies in New Zealand and even for industry bodies and government. It is highly reliant on a detailed national database of accident severity and frequency that can be associated to particular building elements. It is also reliant on finding a way to collate the expert knowledge from experienced practitioners on risk control measures. At this point in time such a system is not seen as feasible for New Zealand, though we should work to ensure that a detailed database of accident severity and frequency is developed that could support such a system. What would be recommended in the New Zealand context is to utilise knowledge management systems within companies and professional bodies to collect and disseminate the expert knowledge of risk control measures for hazards.

5. Conclusions

The systematic literature review of BIM used for Health and Safety in the design stage identified 44 research papers. Categorising the research identified three major technological approaches being considered. These were: safety rule checking systems; formalised safety in design knowledgebases; and risk assessment in BIM. Of the three the work on safety rule checking systems has been identified as the most mature with checking engines available commercially (e.g., Solibri Model Checker), though needing to be developed with applicable codes and standards from New Zealand to be usable by industry. The formalised safety in design knowledgebase and risk assessment in BIM both require a major government or industry initiative to gather the expert information that would be required to make either feasible. In the current climate it does not appear that there would be the resource to develop these approaches to the level required to have a major benefit in the industry. Coverage for specific issues (e.g., fall from height management) could be developed, as shown in various research papers, but this would be a very small part of the needs of the industry.

What was utilised and necessary in the majority of research papers were tools that provided strong visualisation of issues in the design stage. These visualisations are possible with commercial tools and would be immediately beneficial to the industry. The visualisations are integral to support collaboration within the project team and to have many stakeholders involved in risk identification and mitigation during the design stage. We would recommend developing practices which support visualisations and analyses of the following nature: 3D and 4D visualisation of a project to allow all participants to collaborate in interrogating the evolving design for H&S issues; the generation of safety and evacuation plans from the 4D BIM model; and the use of 4D BIM and the work breakdown structure to schedule installation of safety measures.

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