Graduate School of Engineering and Digital Sciences
(Civil and Environmental Engineering)

Application of DfS-Based BIM for Safe Facility Management of Buildings
(Master's Thesis)

Student: Damir Kalzhigitov
Student ID: 201835270
Lead Supervisor: Professor Abid Nadeem
Co-supervisor: Professor Alfrendo Satyanaga

2025

Acknowledgements

I would like to express my sincere gratitude to my lead supervisor, Professor Abid Nadeem, for his invaluable guidance, support, and constructive feedback throughout the course of this research. His expertise and mentorship were critical to the development and completion of this thesis.

I am also deeply thankful to my co-supervisor, Professor Alfrendo Satyanaga, whose insights, encouragement, and academic input greatly enriched the quality of this work. I am grateful for the time and effort both professors dedicated to supervising this research and for providing me with the opportunity to explore an area of study that I am passionate about.

Their support has not only shaped the outcome of this thesis but also contributed significantly to my academic and professional growth.

Abstract

This research explores the integration of Design for Safety (DfS) principles with Building Information Modeling (BIM) to enhance safety in facility management (FM) throughout the lifecycle of buildings. The purpose of the study is to develop a framework that enables early detection and mitigation of risks associated with poor design and construction practices, particularly during maintenance and operations. The significance of this work lies in its focus on minimizing FM-related hazards, which are often underrepresented in conventional safety management systems. A comprehensive methodology was employed, including a PRISMA-guided literature review, development of a DfS knowledge library, semantic enrichment of BIM, and the creation of a BIM-integrated risk register. In addition, machine learning and Dynamo scripts were used to analyze historical accident data and facilitate real-time safety monitoring. Key findings include the successful integration of DfS rules into BIM, enabling the automated identification of maintenance hazards and the visualization of high-risk zones within 3D models. The study also demonstrates that combining BIM with technologies such as 4D simulation and machine learning improves decision-making, risk mitigation, and project efficiency. This research is novel in its emphasis on FM-specific risks and its application of semantic enrichment to enhance BIM-based safety management. Practically, it offers a scalable framework that facility managers and designers can implement to reduce injuries, ensure regulatory compliance, and enhance safety culture across building operations. The approach is particularly relevant for emerging markets like Kazakhstan, where digital transformation in the construction sector is ongoing.

Keywords: Design for Safety (DfS), Building Information Modeling (BIM), Facility Management (FM), Semantic Enrichment, Risk Register, Construction Safety, Maintenance Hazards

Table of Contents

Chapter 1 - Introduction.. 5
1.1. Overview.. 5
1.2. Thesis Statement.. 6
1.3. Research Objectives.. 6
1.4. Novelty, Significance and Impact.. 6
Chapter 2 - Literature Review of the Relevant Research.. 8
2.1. Safe Facility Management of Buildings.. 8
2.1.1. Comparison of methods used to predict and mitigate risks in Safety management 11
2.2. Building Information Modelling Tools for Safety.. 12
2.3. DfS-based BIM model.. 14
2.4. BIM-Integrated Risk Register.. 20
2.5. Advancements in Digitalization: Case Studies from China and Kuwait.. 22
2.6. Risk Evaluation and Alternative Research Approach.. 25
2.7.Machine Learning for Accident Prediction in Construction Safety.. 33
2.8. Synthesis of Literature Review.. 35
Chapter 3 - Methodology.. 42
3.1. Literature review following PRISMA guidelines and VOSViewer visualization.. 42
3.2. Design for Safety-Based BIM Framework.. 44
3.3. Keeping Records of Accident Cases.. 46
Chapter 4 - Results and Discussion.. 50
4.1. DfS Knowledge Library Creation.. 50
4.2. Integration of DfS Knowledge into BIM Platform.. 50
4.3. Clash Detection Analysis and Model Checking using Tekla Structures.. 51
4.4. The use of ML for construction safety.. 54
Chapter 5 - Conclusions.. 58
5.1. Implications of the Research.. 58
5.2. Justification of Achieving the Objectives and Conclusions.. 59
5.3. Future Recommendations.. 60
References.. 60

Chapter 1 - Introduction

1.1. Overview

Despite the progress made in technology, safety gear, and training, construction workers still face a significant number of both deadly and non-deadly injuries and accidents. Even though construction employs only 6% of the American workforce, it is responsible for over 20% of worker fatalities across the nation (OSHA, 2022). This substantial difference highlights the ongoing need for consistent initiatives to improve workplace safety in the construction industry. Numerous research studies have shown that a notable portion of accidents and fatalities in this sector can be linked to insufficient design.

In the three largest U.S. states, between 2000 and 2002, 22 % of injuries were linked to issues during the design phase (OSHA, 2022). Moreover, from 1990 to 2003, design-related problems were responsible for 42 % of construction-related deaths across the nation (OSHA, 2022). From the research that was conducted in Europe in 1991 which further emphasized that 60 % of fatalities resulted from decisions made before starting the site work (Gambatese, 2005). These findings and statistics collectively suggest that by integrating considerations for construction safety into their designs, experts in design can significantly reduce injuries and fatalities in the construction sector.

Improvement in safety management is a pressing concern for the global construction industry, and experts are actively seeking for the innovative concepts and more progressive and innovative technologies. One of the ways of improving safety management is the concept of "design for safety" (DFS) or Prevention through Design (PtD), which means integrating safety considerations throughout the design process. Progressive digital tools, particularly Building Information Modeling (BIM), have emerged as effective methods to advance safety management. For instance, Sijie Zhang et al. (2013) developed an automated safety rule-checking system for Building Information Models, enabling the identification of safety issues and the implementation of precautions before construction begins (Zhand&Teizer, 2013). H.L. Guo et al. (2014) introduced a real-time location and safety warning system for construction site employees, incorporating BIM technology to enhance safety management and reduce accident rates (Hong-lin, 2014). Additionally, Salman Azhar and Alex Behringer (2013) argued that the use of BIM technology can enhance occupational safety by providing detailed site layouts and tools for organizing plans, site data, and communication related to safety planning among construction workers (Azhar&Behringer, 2013).

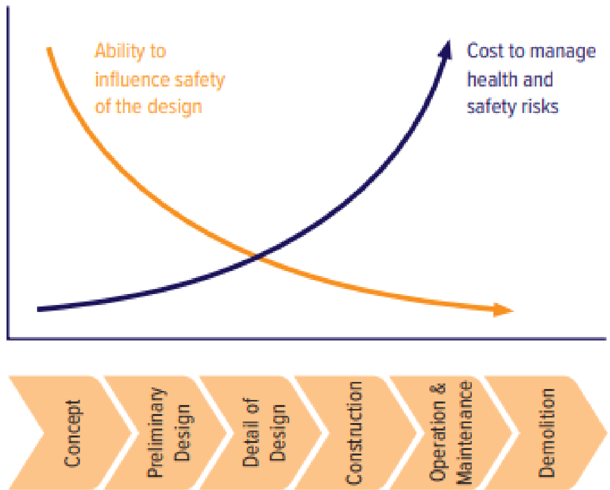


Figure 1. Symberszki chart of influence over a product's life cycle.

Construction Project Safety Planning by Symberszki, R., (1997). *TAPPI Journal, 80* (11),69–74. Safety in design section, Figure 1

1.2. Thesis Statement

Manually identifying hazardous designs remains challenging due to the dynamic and complex nature of construction projects and the diverse safety standards in place. To address this challenge, the paper suggests the potential of a framework built on BIM and safety rules that can automatically detect risky designs based on accident data and make necessary corrections.

1.3. Research Objectives

The primary focus of this study revolves around two key research questions aimed at developing a safe Facility Management system:

1. How do Facility Management (FM) hazards and safety issues correlate with inadequate design and construction/installation practices?
2. Can BIM integration with semantic enrichment enables an intelligent risk review system for safe Facility Management?

1.4. Novelty, Significance and Impact

There will be a new maintenance safety knowledge library related to deficient design and construction/installation so that control measures can be taken early in the design and followed by construction, operation and maintenance. After that, semantic enrichment of BIM will be done for safe FM with the ability to inferencing/processing complex rules with 3D visualization and comprehensive safety knowledge. The BIM-integrated risk register would be an accessible repository for the facility owner and FM personnel to keep a record of all safety issues, actions taken, responsible person and any suggestions/recommendations for future action. The research project aims to eliminate or at least minimize the risk of accidents for maintenance and repair works during the life cycle of facility management. This ability will prevent work-related fatality, injury and illness ensuring a safe working environment, increasing worker's morale and saving accident-related economic loss.

Chapter 2 - Literature Review of the Relevant Research

In this section, the existing published literature related to enriching Design for Safety (DfS) are investigated by using Building Information Modeling (BIM) for safe facility management of buildings and thoroughly analyzing the data of accidents that occured on site to create a BIM-Integrated Risk Register. The invention of Building Information Modelling is one noteworthy technological innovation that has had a significant influence. It is being utilized more and more to improve task performance, particularly in the construction industry. There are inherent risks associated with the construction industry, so multiple studies have suggested that BIM is an essential tool for effectively improving workplace safety.

Fargnoli and Lombardi (2020) performed a radical evaluation of new research that concentrate on the usage of BIM to enhance security at building tasks. The findings of the research harassed the significance of integrating design for safety ideas into BIM and highlighted dynamic visualization and comments as areas for destiny investigation. They had a study additionally emphasized the importance it is to combine BIM techniques in numerous domain names, consisting of safety training and schooling, using BIM to beautify protection manner of lifestyles and resilience, and using quantitative danger evaluation to resource protection manage (Fargnoli and Lombardi, 2020).

2.1. Safe Facility Management of Buildings

Facility Management (FM) is a process that continuously extends throughout the entire lifespan of a constructed facility. Given that these facilities can have a long life, sometimes spanning 50 years or more, a significant 85% of the total project expenses are allocated to their operation and maintenance over their lifetime (Teicholz, 2004). Furthermore, building systems worldwide are becoming increasingly intricate, incorporating advanced technologies for functions like operation, building automation, security, and sustainability. This complexity poses considerable challenges for effectively managing and operating these facilities (IFMA, 2007).

As a result, the maintenance and repair demands associated with these facilities during their FM life cycle carry a significant risk of accidents such as crushing, causing injuries, falls, electric shocks, cuts, and bruises for both workers and facility users. Considering the case for a country with an advanced construction sector, the rate of injuries and illnesses in the field of FM in the USA is significantly exceeding the nationwide average across all other sectors, as reported by the Bureau of Labor Statistics (U.S. Department of Labor, 2022). Although Kazakhstan focuses FM's importance particularly on the correct methods and procedures to be followed, it is evident that safety issues are not integrated into them adequately. What we should understand here is that without safety nothing can be achieved through FM. Currently risk mitigation efforts in relation to FM only include job specific trainings and checklists use but this have been found wanting as they can easily be overlooked thus leading to human error when checking. According to Nancy Leveson and his team, in most of the cases the human error is responsible for between 70% to 80% of all accidents that occur during operations (Leveson, 2004).

Various research indicates a strong link between design and maintenance, where design shortcomings can lead to increased maintenance needs. According to Ganisen et al. (2015), Dr. Shubashini Ganisen and her associates have shown that one can easily achieve economical building maintenance by considering design aspects at the beginning. 40% of maintenance problems came from design, another 30% were construction or installation related and the remaining 30% stemmed from maintenance management according to Lam's research in 2001. Despite being nearly two decades old, Lam's research findings remain largely unchanged. Studies and evaluations of construction accidents indicate that as much as 60% of these incidents could have been avoided through improved design planning (Gambatese et al., 2008). Called "prevention through design" (PtD) or "design for safety" (DfS), this tactic is not widely used in facility management (FM) but largely focuses on enhancing safety during construction.

Safe facility management of buildings can be achieved through many ways that use advanced technologies. Integrating the term of a "design for safety" into the construction sector can be readily done by facilitating the communication between team members and re-creating the model and digital twin of the project to keep track of the progress of the project by using and updating the digital twin by real-time data information. There are also possible ways of using machine learning to achieve the term of a safe facility management of buildings and this thesis will cover the use of BIM and other technologies integrated into BIM to create a flexible framework that can be used in the future construction projects to enhance the safety without losing on economy and time.

In an effort to minimize industrial accidents, Moatari-Kazerouni et al. (2015) incorporated occupational health and safety considerations into the design of facility layouts. Still, this approach was mainly employed for planning facility layout only. Given that different areas such as electrical systems, HVAC systems, plumbing systems and fire protection systems may all fall under one roof when it comes down to facilities management; integrating safety information effectively becomes difficult (Wetzel & Thabet, 2015).

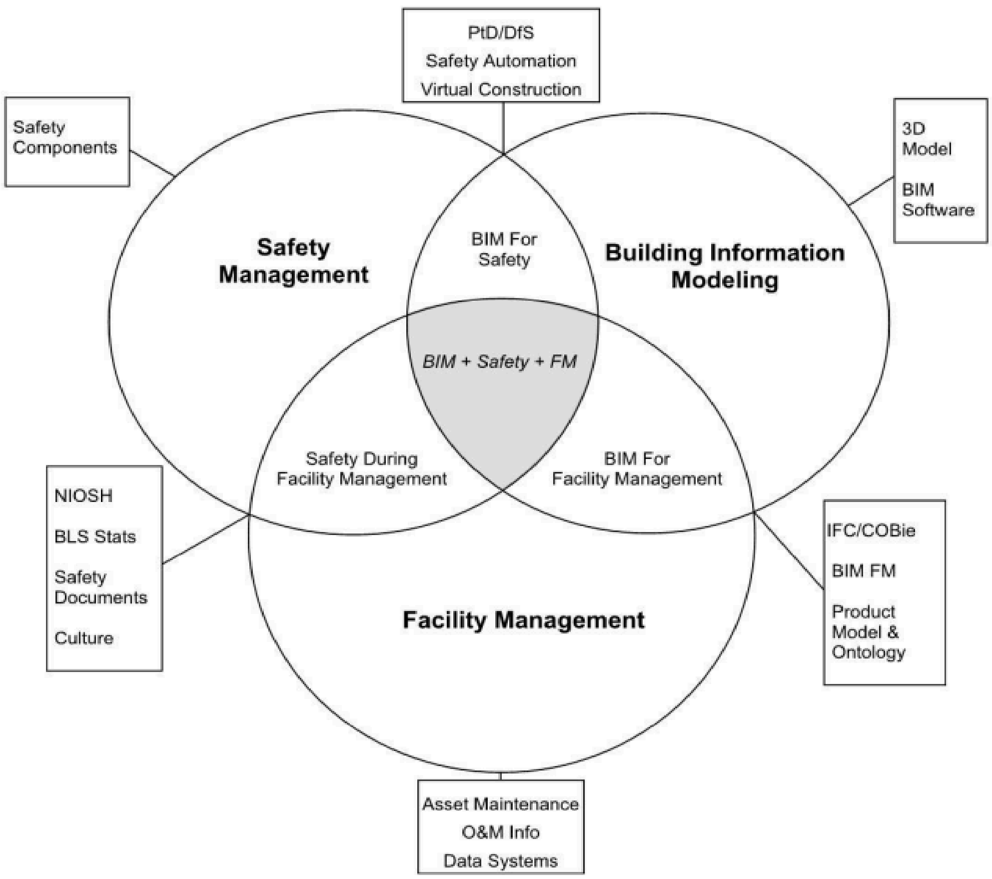


Figure 2. Literature analysis Venn Diagram by Wetsel and Thabet (2015)

In Wetzel and Thabet's (2015) study, the primary focus revolves around detecting, classifying, transmitting, and disseminating safety-related information to employees in facility management.

The authors suggest organizing safety inputs by consolidating diverse data into a unified storage system through the utilization of software programs and research methodologies. The authors set an objective to create a comprehensive, task-specific safety plan by establishing a single data storage system which is similar to the objective I set for this research paper.

2.1.1. Comparison of methods used to predict and mitigate risks in Safety management

There are four main technologies apart from building information modelling that are widely used in detecting and mitigating the risks associated with construction sector. These four technologies are machine learning, digital twins, OHS methods and 4D BIM. These technologies are evaluated based on different criterias which are:

- Detection and mitigation of accidents/risks
- The ability to integrate into the current operations in site
- The technology implementation costs
- The suiltability of technologies for different types of projects and flexibility over time to the changes done in the project

Machine learning is used in construction for analysis and prediction of accident types but it has limitations such as the quality and quantity of data and a hard time integrating into real time construction. The variables and parameters are from the standards set by industry and from the studies on implementation of ML into construction sector. The technology 4D BIM is used as a virtual timeline for construction. It has limitations such as the high costs and hard to implement. The parameters to use this technology is mostly derived from case studies and literature from journals. The technology digital twins which has become popular in recent years is used to monitor the site in real-time. Its main focus is primarily on tracking the progress in construction. OHS methods are often used to validate the design based on rules. This technology is mostly depends on each project and cannot always be implemented into all projects.

Table 1

Comparison of methods used to predict and mitigate risks in Safety management

Technology	Uses in Safety Management	Limitations	Benefits of BIM	Source of Parameters
Machine Learning	Predictive analysis of injury types and occurrences	Limited by data quality and integration into real-time site operations	Enhances predictive safety measures, integrates with real-time monitoring for more effective prevention	Derived from industry standards and recent studies on ML in construction safety (1)
4D BIM	Reference models for safety planning	Complexity in implementation, high upfront costs	Facilitates dynamic simulation of construction processes and proactive risk management	Based on construction management literature and case studies (2)
Digital Twins	Real-time monitoring of construction progress	Focuses mainly on progress tracking rather than risk management	Provides a holistic view, supports proactive interventions and continuous adaptation to on-site changes	Compiled from digital twin technology applications in construction (3)
OHS Methodologies	Rule-based control and design validation	Often project-specific and not adaptable to varying project needs	Standardizes safety protocols, integrates design and operational safety measures more seamlessly	Sourced from OHS regulatory frameworks and safety management guidelines (4)

The data for each of the technologies are gathered from the articles published in journals, reports from industry and appropriate implementation in real world projects. Each of the technologies has its own strengths however BIM can be easily implemented into construction projects combined with all of these listed technologies. As an example can be set a model framework that implements both BIM and ML when there is a data prediction that is updated non-stop greatly improved with real-time data.

2.2. Building Information Modelling Tools for Safety

Building Information Model (BIM) acts as a tool which can store the most current information about a built facility (Kivits and Furneaux, 2013). Furthermore, it has proved effective in managing construction safety on-site. Over the years, however, BIM has been used more in the Architecture, Engineering, and Construction (AEC) industry than in operation, maintenance and facility management (FM) where its usage is limited (Becerik-Gerber et al., 2012). Nonetheless recent studies show that BIM can greatly improve FM practices (Cheng et al., 2017; Pishdad-Bozorgi et al., 2018).

Building Information Modeling means creating a digital model with accurate geometry and relevant information that supports the whole life cycle of a building from construction through to facility management. Most studies advocate for early integration of BIM into a project; it is now widely adopted during design and construction stages at the expense of traditional 2-D drawings and CAD packages which are slowly being phased out. Although the term "building information modelling" has been around for two decades or so, the concepts and methods associated with this approach were introduced about 35 years ago. This ability of BIM's has grown significantly over time due to technological advancements.

Although Design for Safety (DfS) has been recognized for around 25 years, the use of BIM tools for safety is a relatively recent concept, and research in this area is still in its early stages (Gambatese et al., 2005). As demonstrated by Ku and Mills (2010), BIM has the potential to "create a built environment that seamlessly integrates safer construction practices" by identifying hazards early in the design process and optimizing for safety (Ku and Mills, 2010).

The research study by Sacks et al. (2017) presented the SeeBIM 1.0 prototype to add useful data to a digital building model. For the estimation of object kinds, identification, and systemic aggregation, Semantic Enrichment Engine for BIM, the SeeBIM prototype program incorporates specialized knowledge in machine rules. It cannot be assured that its rule sets are adequate because it is restricted to axis-aligned bounding box geometry (Sacks et al. 2017). The parametric representation of BIM that contains only the geometry, location, and orientation of 3D shapes (Sacks et al. 2017), often requires semantic enrichment through domain-specific vocabulary, domain knowledge, and information exchange for a specific application (Aram, 2014; Zhong et al., 2018; Simeone et al., 2019). An ontology is to be developed to process the FM-related safety rules due to deficient design and construction/installation.

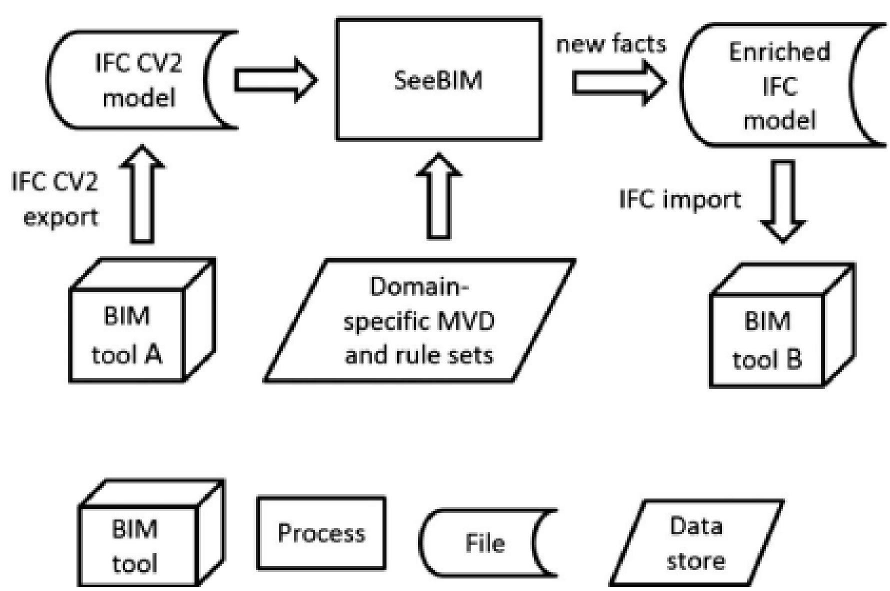


Figure 3. SeeBIM process algorithm explained as a chart.

Note: IFC CV2 files conform to the Coordination View 2.0 model view definition. Semantic Enrichment for Building Information Modeling: Procedure for Compiling Inference Rules and Operators for Complex Geometry by Sacks et al., 2017, *Journal of Computing in Civil Engineering, 31*: 04017062. Previous Work section, Figure 1 (https://doi.org/10.1061/(ASCE)CP.1943-5487.0000705)

There is another paper by Hongling et al. (2016), that discusses the ways to integrate BIM with safety rules. This paper suggests that the tool to collect and manage the data connected to buildings and the construction process must incorporate safety regulations and construction information. Hongling (2016) and other specialists have conducted an interesting experiment by designing a test platform customized by combining Revit and Unity 3D. The strategy below depicted in Figure 4 was tested using the windows of a four-story structure as an experiment. Autodesk Revit was originally used to create the building's BIM model. Module ID was set up for each component throughout the modelling phase (Hongling et al., 2016). It is very simple to extract additional properties from a BIM model, such as location and size. The building information model was then loaded into Unity 3D, which was used to connect design safety regulations.

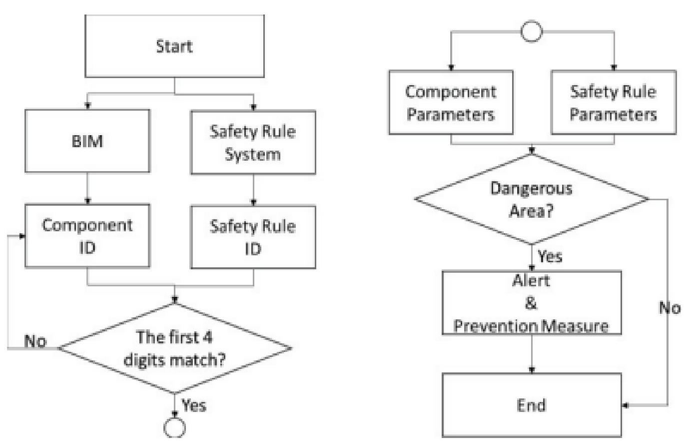


Figure 4. Identification of dangerous design elements automatically using BIM and safety regulations

2.3. DfS-based BIM model

The concept of DfS is effective as a preventive measure for construction, operation, and maintenance and it has been receiving growing attention in recent years (Gambatese et al., 2005). Nevertheless, the DfS implementation is still in its infancy and most of the efforts have been paid to preventing construction-related hazards and little has been done to manage FM-related hazards through proper design consideration (Gambatese et al., 2008; Hossain et al., 2018). Hossain et al. (2018) considered a few simple operation & maintenance-related hazards that can be addressed through proper design considerations (Hossain et al., 2018). For instance, the risk of "fire escape" can be avoided with appropriate window opening; designing a window with swinging property would enable easy cleaning and maintenance from inside of the building, which eventually would reduce the risk of "fall from height"; and so on. Still, it's miles very vital to behavior an in depth investigation of ways numerous Facility Management (FM) activities present dangers and hazards, in addition to their connections to design or production shortcomings, considering the intricate interactions amongst numerous disciplines like mechanical, electric, plumbing, HVAC, fireplace protection, and greater.This study sets a goal to use the Design for Safety (DfS) concept to integrate safety knowledge into Building Information Modeling (BIM) to assess maintenance risks in FM. The proposed system is fundamentally integrated into the BIM model which will include two Safety Knowledge libraries that can be fully updated, allowing for additions, modifications, and deletions. These libraries can be independently examined alongside any BIM model and serve as a repository of safety knowledge.

A research paper by Xiaer et al. (2016) provides an outline of Design for Safety (DfS) and Building Information Modeling (BIM) independently before proposing their integration to mitigate accidents. The study examines how using BIM in the construction industry can improve safety management. The conclusions drawn are based on a case study conducted during a significant redevelopment project in Manchester, United Kingdom. The study reveals an enhanced comprehension of the potential advantages of BIM for FM operations and the management of lifecycle data (Codinhoto and Kiviniemi, 2014). It also allows designers to easily access safety information through BIM-based tools, making it easier to apply DfS principles.

Additionally, combining DfS and BIM gets rid of limitations from traditional project approaches and encourages better collaboration among different project stages (Xiaer et al., 2016).

Codinhoto and Kiviniemi (2014) discussed several problems that are related to the adoption of Building Information Modeling (BIM) in Facility Management (FM) and enumerated various uses, indicators, and benefits linked to it. The conclusions of the research are primarily based on a case look at carried out at some point of huge re-development venture in Manchester, United Kingdom. The study is a famous and a more desirable comprehension of the capability advantages of BIM for FM operations and the control of lifecycle data (Codinhoto and Kiviniemi, 2014). Although there are limitations to implementing BIM in projects, the benefits of integrating BIM technologies into FM readily outweigh them. Advantages during the design and construction phases include:

- The support in decision-making
- The reduction of hazards and errors at the construction site

The simulations suggest several potential benefits in terms of:

- The savings in time
- The management of personnel
- The cost savings

The maintenance process leads to:

- The reduced service interruptions
- The enhanced support for core business functions
- An improved customer satisfaction.

Salzani et al (2024), proposed a methodology that integrates BIM technology with principles of design-for-safety and facility management to improve the risk identification and mitigation of risks throughout the construction process. This methodology consists of three main stages which are preliminary analysis, design and execution stages. These stages are followed by appropriate tools and techniques.

First stage includes the BIM model creation and the LOIN analysis. The model should be checked for the stage of completeness and details' level to conduct further analysis for safety. Second stage includes the model validation, analysis of risks related to the design, suitability of the risk matrix to the design, activity analysis and risk mitigation strategies. On this stage occurs the simulation of the interferences with highest risks. After the simulation it is checked for the appropriateness of the risk matrix to the management of construction. The used technologies are the BIM model with an integrated regulations of safety and advanced technologies such as Dynamo which can be used together with Autodesk Revit can be used. Dynamo scripts and 4D BIM can offer an improvements for the sequences of construction management. Construction tasks can be easily sequenced with the use of BIM technologies and which optimizes the construction timeline.

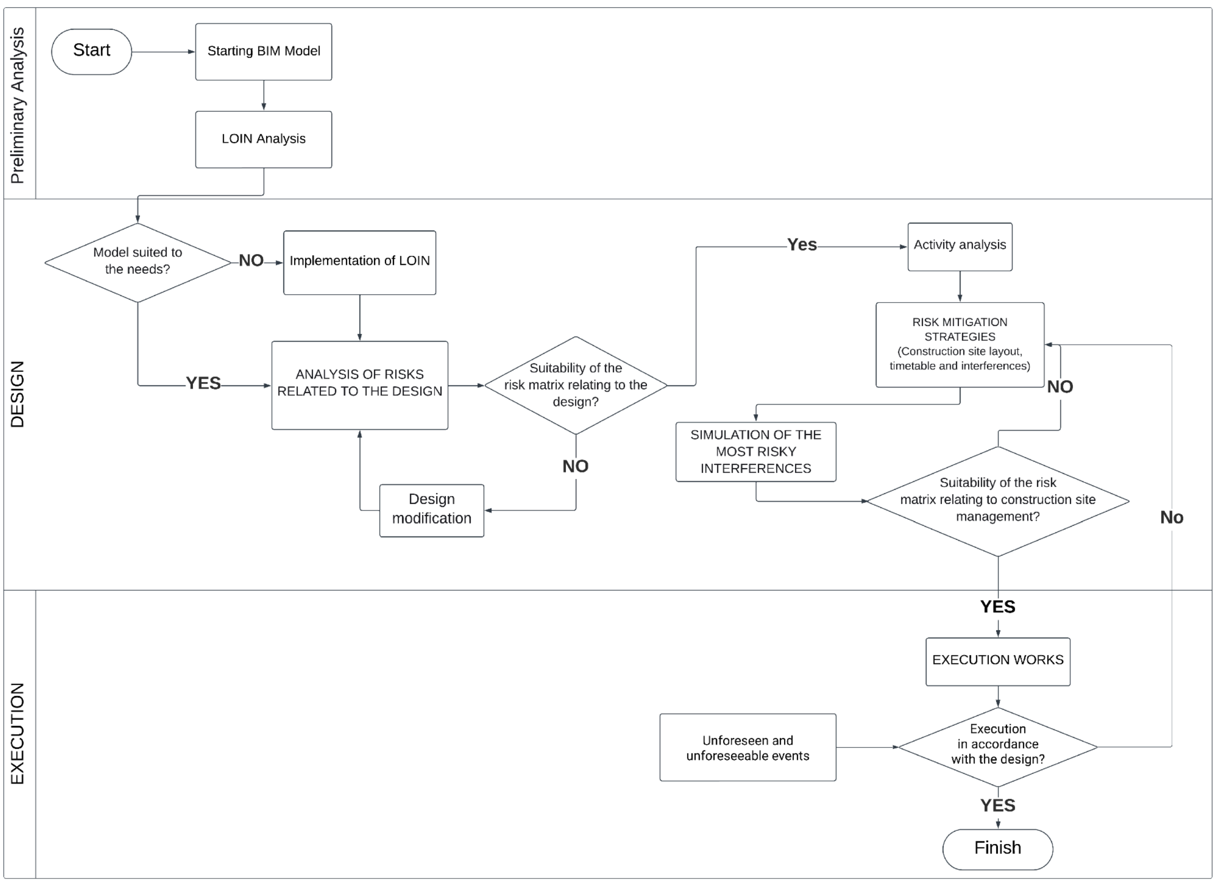


Figure 5. The mechanism including three stages implementing BIM into the construction process proposed by Salzano et al (2024)

Third stage is the execution phase. In the execution phase all the theoretical strategies already discussed in the design phase are applied into the construction site into a practice to check the effectiveness of the methods. The main activities of this stage is the integration of BIM on a real-time basis, monitoring and managing accidents/incidents. Figure 6 shows how the integration of BIM in practice can bring a lot of advantages to safety on site in a very dynamic way.

Salzano et al uses the BIM 360 software to track the construction site in a real time and the first step on monitoring the field is the use of API for BIM 360 which receives data from the field which includes the site workers and site conditions. The received data is further structured with the use of scripts in Dynamo. After this Dynamo script assesses the risks from the received data in real time. Already created site matrix is analyzed with site activities by using the Dynamo scripts. Risk matrix is further modified by the updates done with the integration of scripts into the BIM model. After this occurs reassessment of the risks and the code in a script does the risk mitigation based on the new assessment and factors of risk.

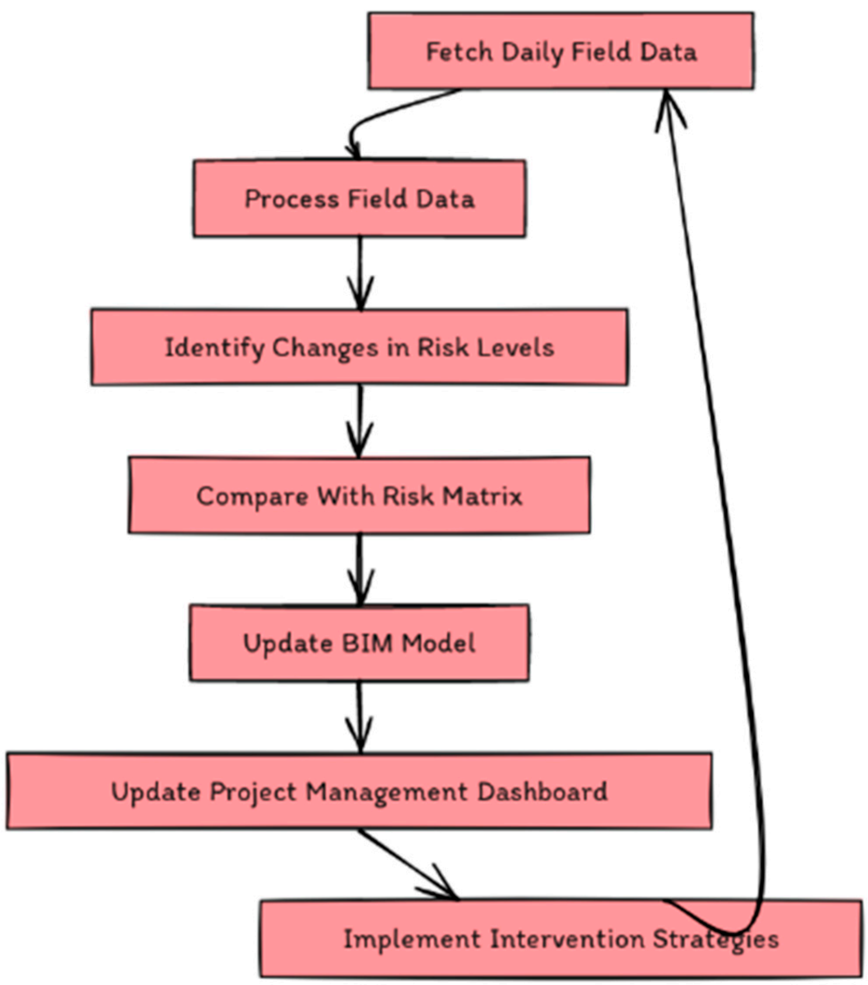


Figure 6. BIM data progression throughout the stages of decision-making proposed by Salzano et al (2024).

The BIM model was developed and adapted to the set LOINs further. To create this model the software used was Autodesk Revit combined with BIM360 to create the detailed digital twin of the Basilica of Santa Croce. To create this model scanning technology with a laser scanner was used to make the detailed layouts for the model which was further put into the BIM model for the analysis. After the creation of the BIM model, Salzano et al (2024) wrote a script in Dynamo making automation process for risk assessment possible and the engineering analysis with historical data was used as a database to conduct a risk assessment. The created model is shown in Figure 7.

The scripts that are written in Dynamo are integrated to BIM360 to dynamically update the information on risk assessment after the new data is imported into the database. Also, 4D BIM simulations were used to create a sequential plan and to make the better use of the provided resources. The data from the real time was being imported into the BIM model constantly after being scanned using BIM360 which significantly cuts the time to make decisions for teams. The advantage given by BIM360 API was that changes that were made had been instantly shown on all the platforms which greatly enhanced communication between different teams responsible for different tasks. In a real project, the approach using BIM integrated with other technologies in all stages of construction proved to be the most efficient as there was zero incidents during the construction.

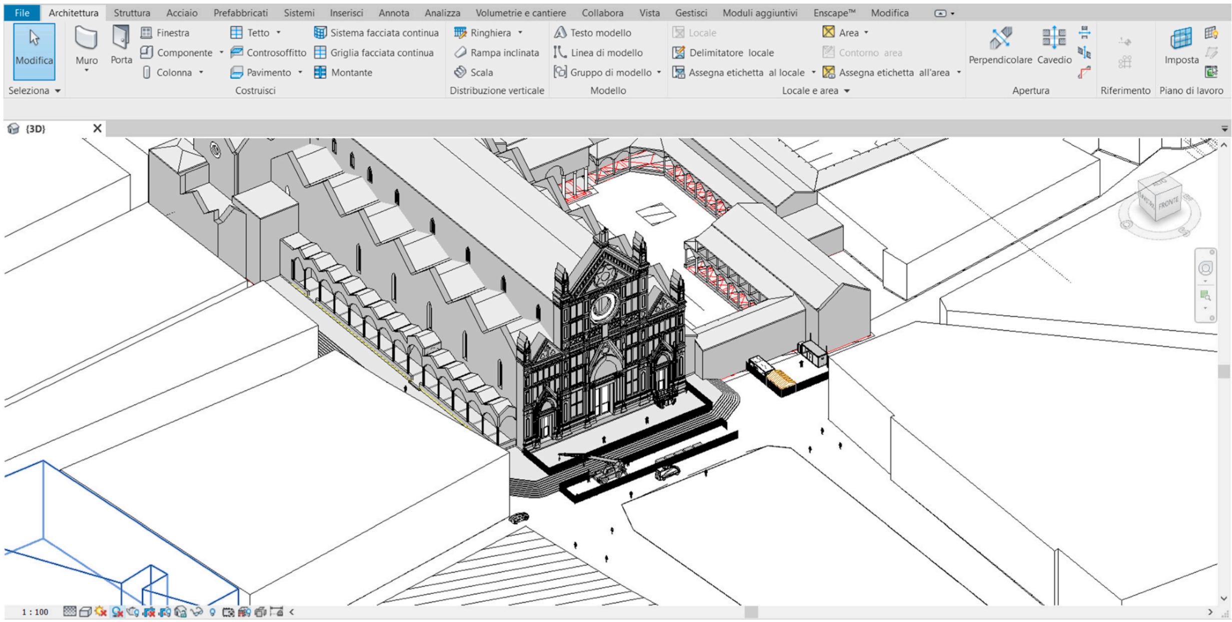


Figure 7. BIM model created by adapting to the Level of Information (LOINs) of the project proposed by Salzano et al (2024)

After the model is done and the data is being updated using the changes in a real time by the aid of BIM, Dynamo scripts and BIM360, the risk assessment data will be exported from the software as csv file. The exported file is shown as a Table 2 with all the risks covered and analyzed by different factors.

Table 2

Risk matrix created and exported from the BIM model shown in Figure 7

Risk Matrix	Falling from Heights Risk	Risks Towards the Outside	Risks of Instability of the Vault and Walls	Risks from the Outside to the Inside	Risks Caused by Specific Processes and Materials Used
Scaffold	16	6	10	12	12
External Pillar 1	4	14	4	16	8

External Pillar 2	4	14	4	16	8
Tympanum	16	16	6	12	8
Marble Slab with Lunette	10	10	6	6	7
Side Column Portal 1 SX	6	8	4	12	7
Side Column Portal 1 DX	6	8	4	12	7

2.4. BIM-Integrated Risk Register

Semantic enrichment of BIM is the process of the addition of domain-specific knowledge to a digital model by technology that infers additional data by analyzing the existing principles (Belsky et al., 2016). To help the processing of acquired knowledge in the BIM environment, pre-processing of BIM is necessary, which will be done with semantic enrichment to provide the information that would be necessary for the FM safety evaluation. An inference rule engine will be developed for the safety knowledge (domain-specific) to identify the new facts about building objects and their relationships. The inference rules are compiled and stored in persistent storage.

The user interface for managing and regulating the identified design and construction-related risks will be provided via the BIM-integrated risk register. It correctly links the risks and mitigation features or other provisions with the BIM version. A manner is covered within the BIM-incorporated chance check-in to guarantee that identified hazards are reduced to acceptable risk tiers. It comprises 3 critical development regions: BIM version integration, danger register talents, and protection process. The risk record can be given to FM workers to follow up on any remaining risks. The BIM model's file format will be IFC (.ifc). Various businesses may construct their BIM models using various BIM platforms (e.g., Revit, Tekla Structure, ArchiCAD etc.). The IFC format would be useful because all systems support import and export in. ifc format. "Eyeshot" will be utilized for database rendering and visualization in the BIM model because it is an OpenBIM platform like IFC and requires less computer capacity (Wetzel et al., 2015). This rendering tool is very useful because the BIM file for a large project might be rather enormous. A case study will be used to validate the proposed project and confirm that the system is fully functional.

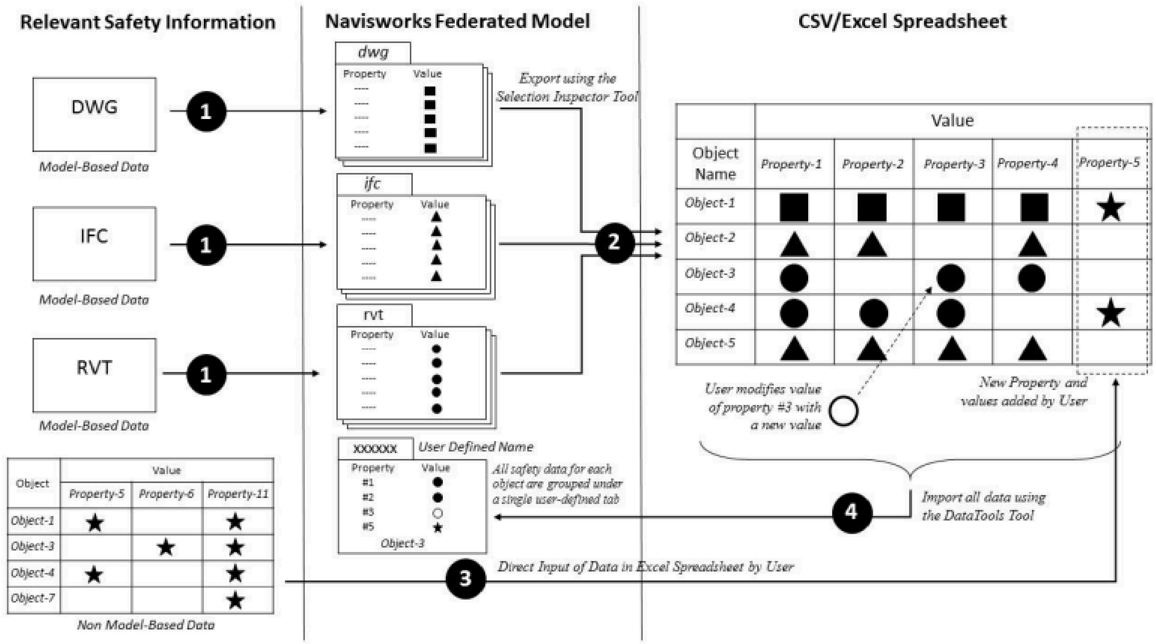


Figure 8. Safety Framework Data Transfer Mechanism

Note: Visually illustrates the comprehensive data transfer system utilized in the safety framework based on Building Information Modeling (BIM). The use of a BIM-based framework to support safe facility management processes by Wetzel, E. M., and Thabet, W. Y. (2015), *Automation in Construction, 60*, 12-24. Data Transfer Mechanism for BIM-Based Safety Framework section, Figure 33 (https://doi.org/10.1016/j.autcon.2015.09.004)

2.5. Advancements in Digitalization: Case Studies from China and Kuwait

As a country that first delved into the digitalization of the construction sector considering the case of China is very essential. There is a paper by Zhou et al. (2022) that quite well sums up all the papers regarding China and proposes a new model of semantic framework development for safe facility management that uses BIM. According to a case of China, after analyzing the previously released statistics that state that the quality of design documentation in China has declined recently, making it difficult to ensure their safety, Zhou et al. (2022) proposed a new DfS-based semantic framework using BIM technology that has shown significant benefits in safety management in resolving this issue because of its object-oriented modelling, digitization, visualization, and other features. The use of BIM technologies is growing faster as a result of the ongoing implementation of regulations and industry standards. Zhou et al. concluded that the DfS process is currently more effective thanks to computer-based ACC technology, but there is still no effective way for semantic and knowledge-based BIM information description during the design stage of building projects. The results of text mining and data extracted from BIM were employed to construct an OWL ontology for Design for Safety (DFS), with Zhou et al. proposing a Natural Language Processing (NLP) approach for managing safety requirements (Zhou et al., 2022). This ontology provided a semantically equivalent representation of the data originating from the design phase in BIM and the information derived from the DFS process (Zhou et al., 2022). This process standardized data from diverse origins, improved data compatibility, and ultimately enhanced the efficiency of automated compliance checks based on DFS (Zhou et al., 2022).

The research via Shahar et al. (2022), wherein the authors tested the layout professionals working in Kuwait's manufacturing area's knowledge of DfS and its use. There is a correlation among designers' DfS attention, training, and schooling and their participation in DfS sports activities. However, different factors together with expert association, education diploma, experience, and business enterprise length do now not notably have an effect on the adoption of DfS strategies. This take a look at contributes to the prevailing studies on DfS adoption within the introduction enterprise, specially focusing on enhancing expertise of DfS amongst layout professionals for the gain of future building projects (Shahar et al., 2022). From the case of the State of Kuwait, it is clear that there is a slow pace of digitalization in the construction sector which leads to the necessity of future research on combining BIM to safe facility management.

Fargnoli and Lombardi (2020) delve into various studies and reports focusing on the utilization of Building Information Modeling (BIM) to enhance safety at construction sites. The paper provides a comprehensive review of research data established since the decade. The analysis shown in Figure 6 emphasizes true data-based responses, integration of BIM for design improvements in warehousing, large-scale applications of BIM, and dynamic design and presentation as a promising method of study. The evaluate gives tips for alternative meaningful uses of BIM, with an emphasis on conservation training and schooling, the blessings of BIM for improving safety residing and resilience has been stronger, and complete danger assessment techniques to better support conservation cease.

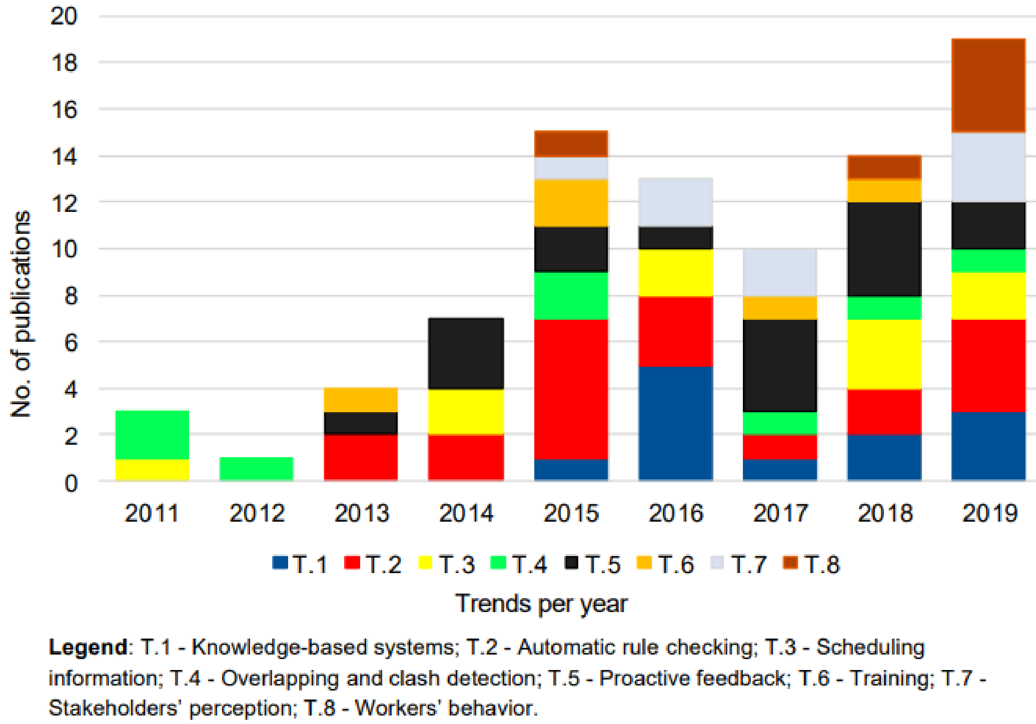


Figure 9. Research targets of publications per year during the years 2011 and 2019 (Fargnoli and Lombardi, 2020).

The Figure 6 shows the results of the paper by Fargnoli and Lombardi (2020) which clearly shows recent trends in solving FM-related issues in the most efficient way. Initially, the findings showed a growing interest in this research domain over recent 5 years. Notably, a majority of studies emerged in the latter half of the examined decade from 2015 to 2019, with only 15 articles reported between 2010 and 2014 (Fargnoli and Lombardi, 2020). While it may seem obvious that such a trend correlates with the increasing availability and potency of information technologies, it's worth highlighting that certain research trends, such as category 1 (knowledge-based systems), category 6 (training tools), category 7 (stakeholders' perception), and category 8 (workers' behavior), have only started to be investigated recently (Fargnoli and Lombardi, 2020). These new research directions highlight the challenges in creating BIM-based OHS solutions, summarized as follows.

One of the main advantages of considering case studies is that it shows other countries' experiences in locally popularising the use of Building Information Modelling not only for scheduling and designing but also using it as a tool for creating automatic rule checking paired with the safety risk library. In a pilot project by Collinge and his team, they proposed to integrate Building Information Modelling into construction safety in an efficient way by testing the proposed methodology all over the UK (Collinge et. al., 2024). The authors created a set of questions to ask construction health and construction safety experts, afterwards this survey was established which was then posted in an online platform. One point to consider from this research is that when participants observed a demonstration of a video of a BIM-based tool they assessed the usefulness of the tools in dealing with safety issues that are present in the construction sector.

Salzano et al (2024) have made a comparison between two timelines before using BIM and after using BIM based on a statistical normal distribution. Authors have decided to choose two case studies to apply BIM technologies into the construction to check the effectiveness of methods on decreasing the numbers of incidents. First case study is the SHiP experiment that is on CERN where the initial purpose was to create a digital twin of the construction site using Autodesk Revit. The use of BIM 360 made the impossible connection between the real time data and digital model a feasible option.

From the figure below (Figure 10), it can be seen that there is a good amount of improvement done on the incidents rate and the construction time. The project duration is greatly decreased along with the number of accidents in construction site after the integration of BIM into the project management.

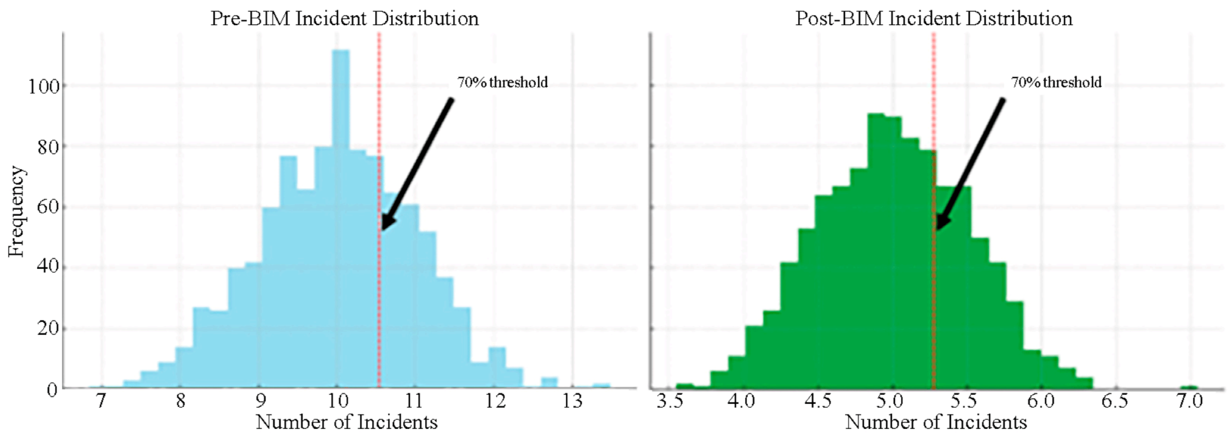


Figure 10. Comparison of accidents before implementing BIM and after integrating BIM on a research done by Salzano et al (2024)

The use of BIM in a construction sector greatly decreases not only the incidents' rate but also it affects the project duration and budget variance compared to the time before using BIM technologies as it is shown in Figure 11. It makes the use of BIM sustainable in many occasions as it improves the workers', budget and time management of the project without sacrificing the quality of the project. Therefore the BIM framework enhanced with other technologies such as 4D BIM and machine learning will be advantageous in terms of safety management, cost managements and project duration.

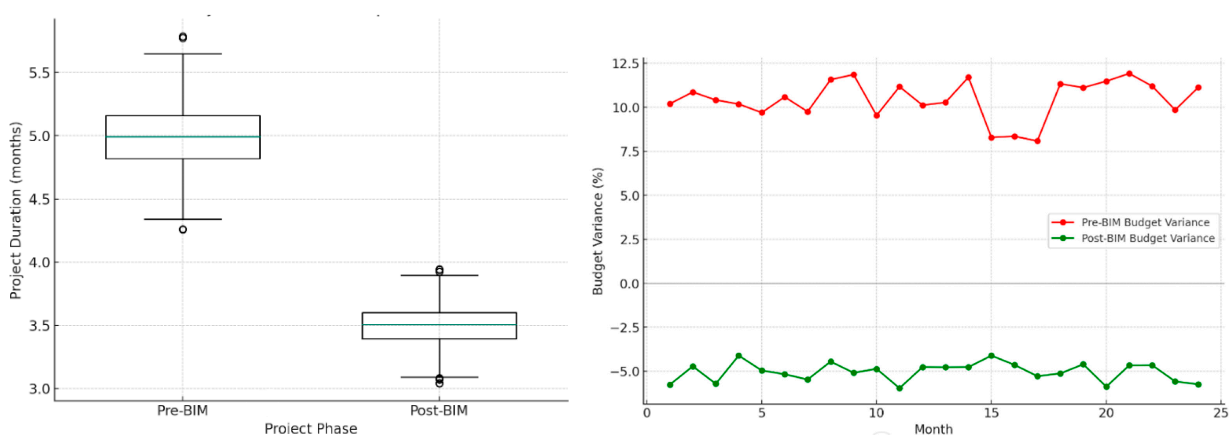


Figure 11. Comparison of pre-BIM and post-BIM on project duration and budget variance on a research done by Salzano et al (2024)

2.6. Risk Evaluation and Alternative Research Approach

Safety knowledge, semantic enrichment, and BIM integrated reasoning engine are the key aspects of this research. Following the simple illustrations provided earlier, correlation can be developed for other FM hazards that are linked to deficient design and/or C/I along with possible mitigation measures/suggestions. As an alternative approach, following the method proposed in Moatari-Kazerouni et al. (2015a, b) for facility layout planning, risk can be assessed for different design alternatives of a building facility taking into account the FM-related activities by that building facility so that the best design can be selected to minimize FM risk. Risk assessment can be done based on the type of hazards, their severity, the likelihood of occurrence, the likelihood of exposure to the hazard, exposure time, the possibility of avoidance etc. Nevertheless, the method could be tedious considering the complex interaction between multiple disciplines of built facilities.

BIM integrated reasoning engine was proposed by Hossain et al. (2018) to parse DfS rules, particularly for construction hazards. A similar reasoning engine can be developed to parse the DfS rules in identifying FM hazards and a BIM-integrated risk register can be developed. However, a challenge could arise in using the BIM-integrated risk register to follow up for the residual risk during the FM lifecycle. BIM has not been fully exploited for O&M and researchers are still working on FM-enabled BIM. Furthermore, necessary training is to be provided to O&M and FM personnel about the BIM process and technologies (Giel and Issa, 2016). Nevertheless, the knowledge library and risk register can be used as stand-alone without BIM. The Case-based reasoning method (Goh and Chua (2009, 2010)) can also be adopted using the knowledge library in identifying FM hazards related to deficient design and/or C/I.

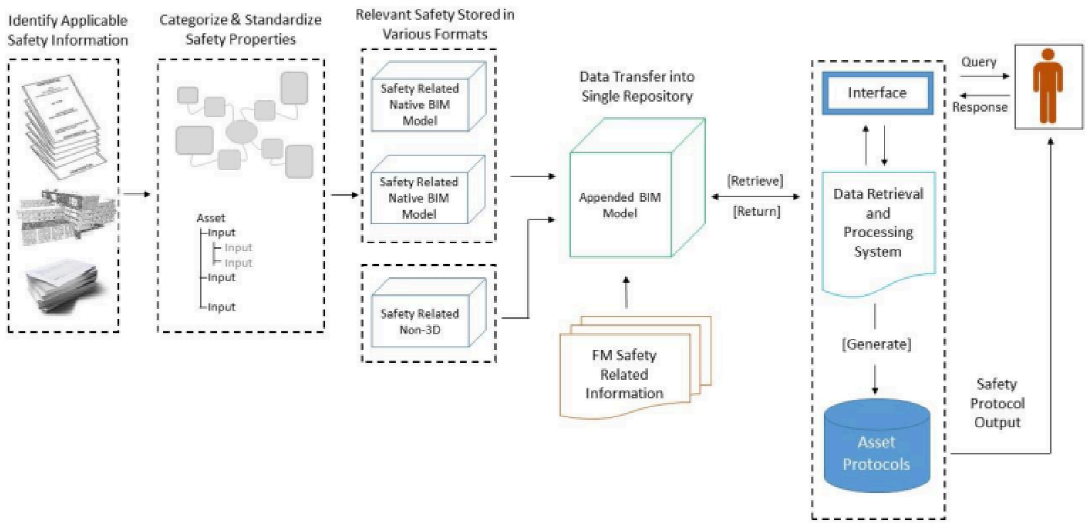


Figure 12. BIM-Based Framework proposed by Wetzel and Thabet (2015)

The Figure 13 shows the steps to create a BIM framework which will be able to integrate the collected data about accident cases. First stage includes identifying the safety information that is applicable to use in BIM. Second stage is to categorize the properties of safety by creating input variables. Third stage is storing the information in different formats of BIM model to further consider exporting the predictions for construction accident cases. After these three stages data is transferred into a single place which is a BIM model.

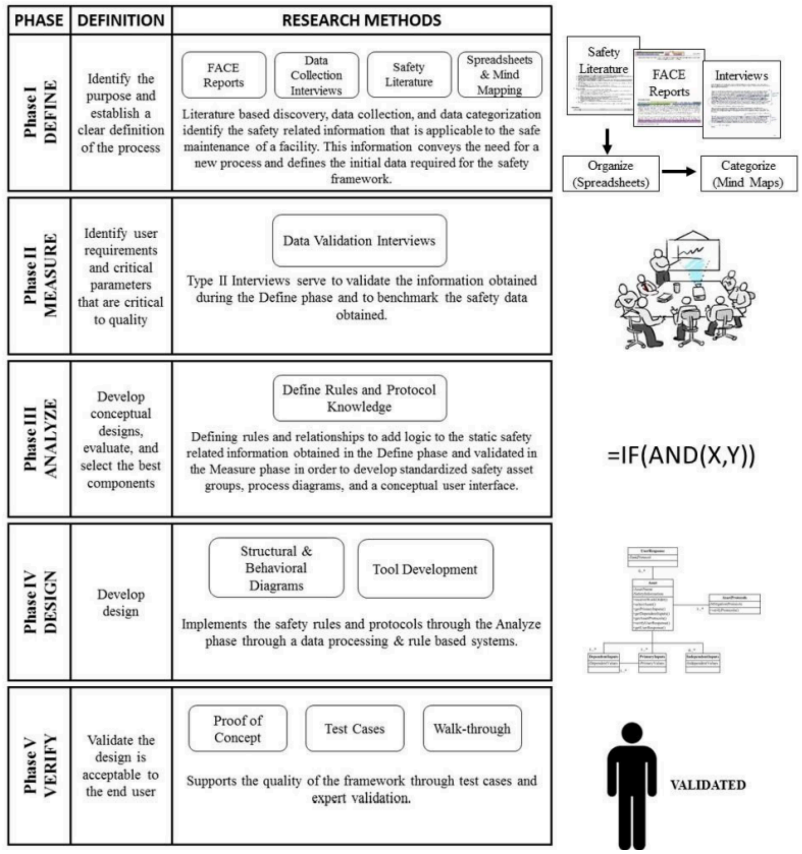


Figure 13. Research Methods used in the DMADV Framework proposed by Wetzel and Thabet

In their paper, Wetzel and Thabet (2015) have set a goal to enhance safety during the facility management phase by consolidating safety-relevant data within a unified BIM-based framework. The methodologies employed to achieve the study objectives are rooted in qualitative analysis, specifically employing a Six Sigma methodological approach which can be further adopted as an alternative methodology to create a single database or can be combined into the proposed BIM-Integrated risk review system. The author introduces the Define - Measure - Analyze - Design - Verify (DMADV) framework as part of the Six Sigma methodology where the authors have specifically provided a detailed explanation for each of the steps (Wetzel and Thabet, 2015).

The research by Kulinan et al. (2024) shows an integration of Building Information Modeling (BIM) and Computer Vision (CV) to create an workforce safety monitoring system at construction sites. The main focus of the research was to enhance the workforce safety by leveraging the real-time capabilities of computer vision along with the spatial context of Building Information Modelling (BIM). The Figure 9 shows the BIM model and the model of the building in the real life. The model in BIM is divided into two zones of safety which are green and red zones. A green coloured-zone indicates a safe area while the red coloured-zone indicates a dangerous area for workers. The methodology consists of computer vision data integration, real-time monitoring, and visualization within BIM, with a purpose to overcome the limitations of studied traditional safety monitoring approaches.

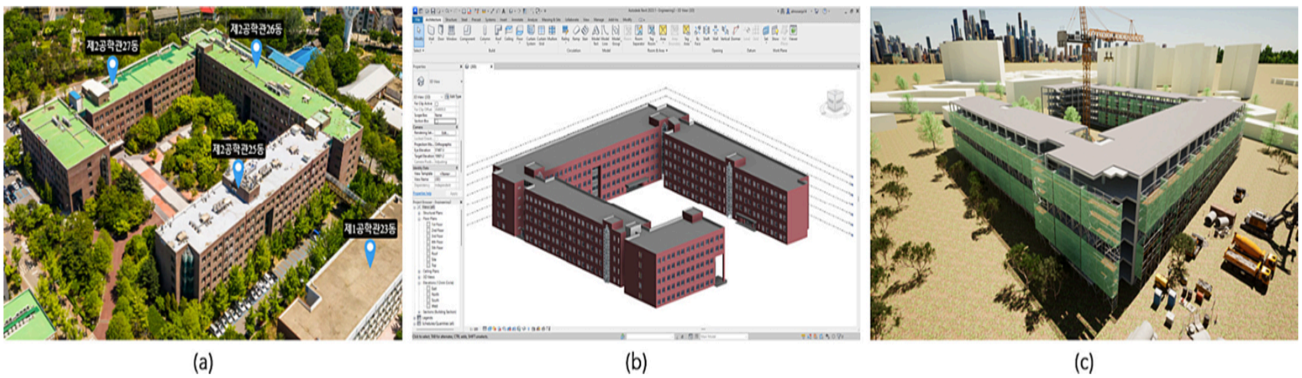


Figure 14. The tested building by Kulinan et al. (2024)

Figure 14 shows the building that was taken as a test material to check their latest algorithm called YOLO. The stage of vision-based module indicates the use of the algorithm YOLO to detect workers' positions from CCTV footage. The workers are classified into four categories depending on the presence of a personal protective equipment. This module also includes tracking the movement of workers using the SORT algorithm, which enables the system to assign each of unique identifiers to each worker and track them continuously, thus allowing for detailed analysis of worker movement and safety compliance (Kulinan et al., 2024). The use of this kind of trackers facilitates the safety management by providing with additional data that is drawn from workers.

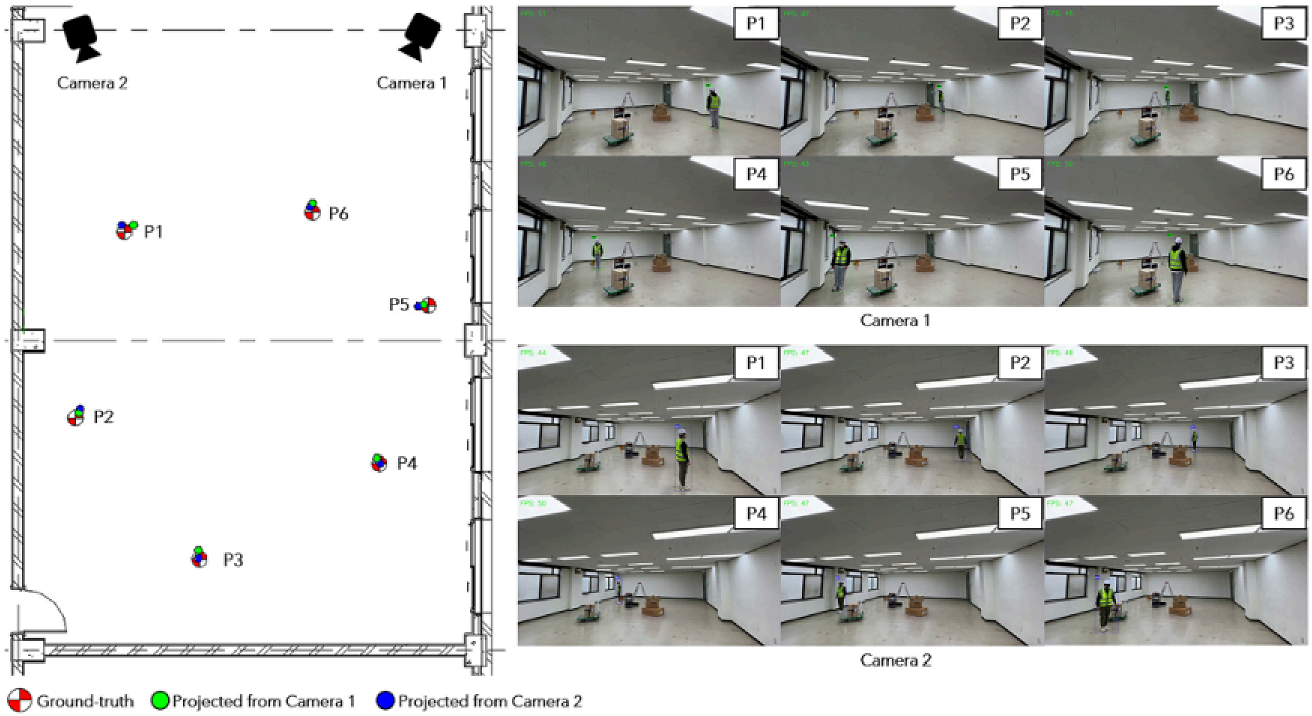


Figure 15. Assessment of the accuracy using two cameras by Kulinan et al. (2024).

The data integration layer used a relational database management system (RDBMS) to connect Computer Vision data with the tools of BIM. The database was designed to store both real-time and historical data about worker movements and safety conditions, enabling the system to visualize both current safety conditions and past data in the database for analysis. The integration facilitated the designed flow of information between the CCTV footage and the BIM model, supporting dynamic visualization of site safety (Kulinan et al., 2024).

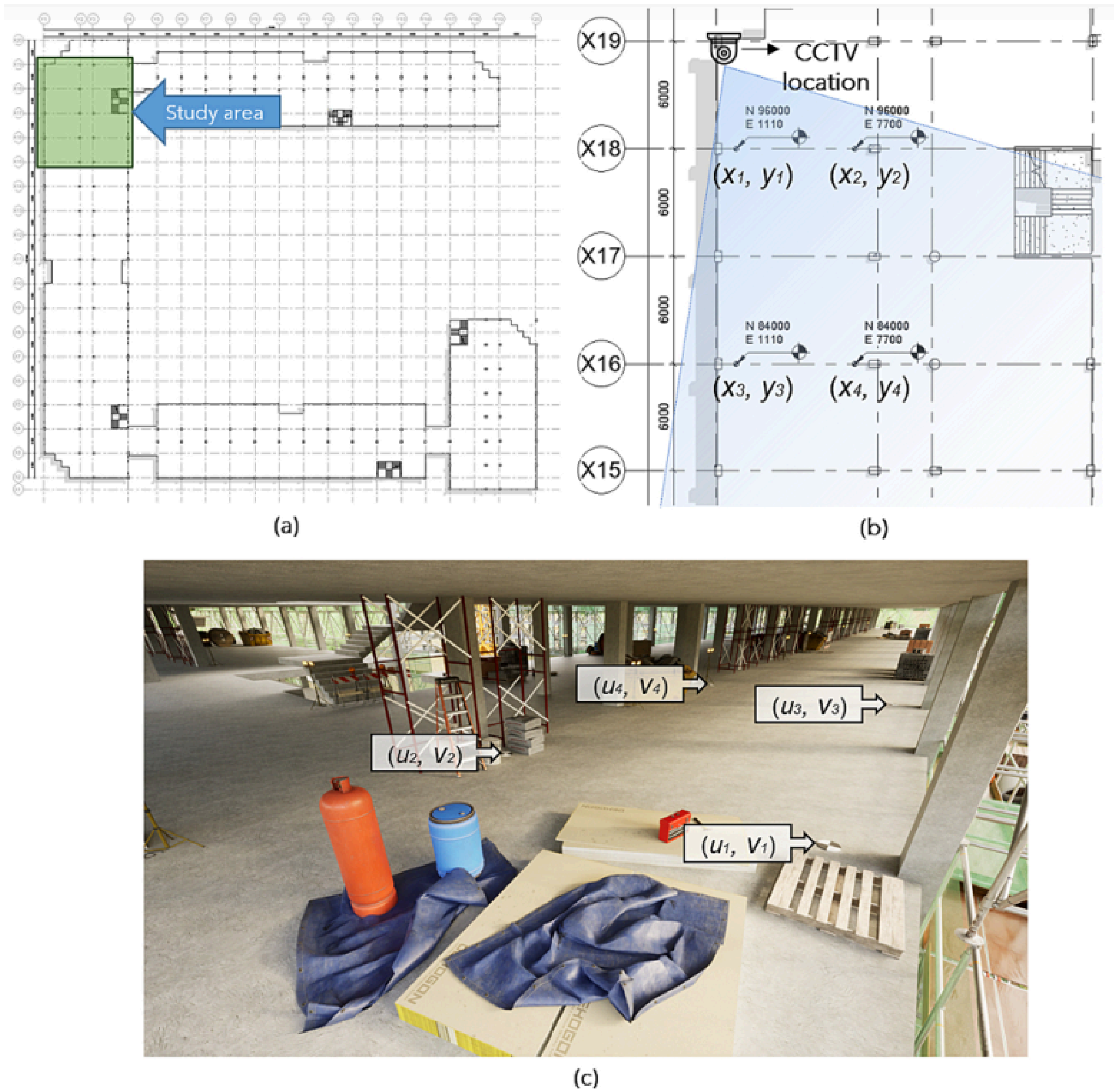


Figure 16. The assessment of four points from different perspectives: (a) Floor plan designed in BIM (b) The area of studied building (c) Visualization of construction area

The BIM visualization layer used the Dynamo visual programming language, which is integrated with Revit, to incorporate the collected data into the 3D BIM model. The system periodically updated worker information and visualized worker locations and safety compliance status based on real-time data captured by the cameras. The visualization included color coded risk assessments for each worker, providing an intuitive visual representation of safety levels that allowed safety managers to take quick action when high-risk situations were detected (Kulinan et al., 2024). This case shows the flexibility of the system designed by Kulinan et al. and proves to be feasible.

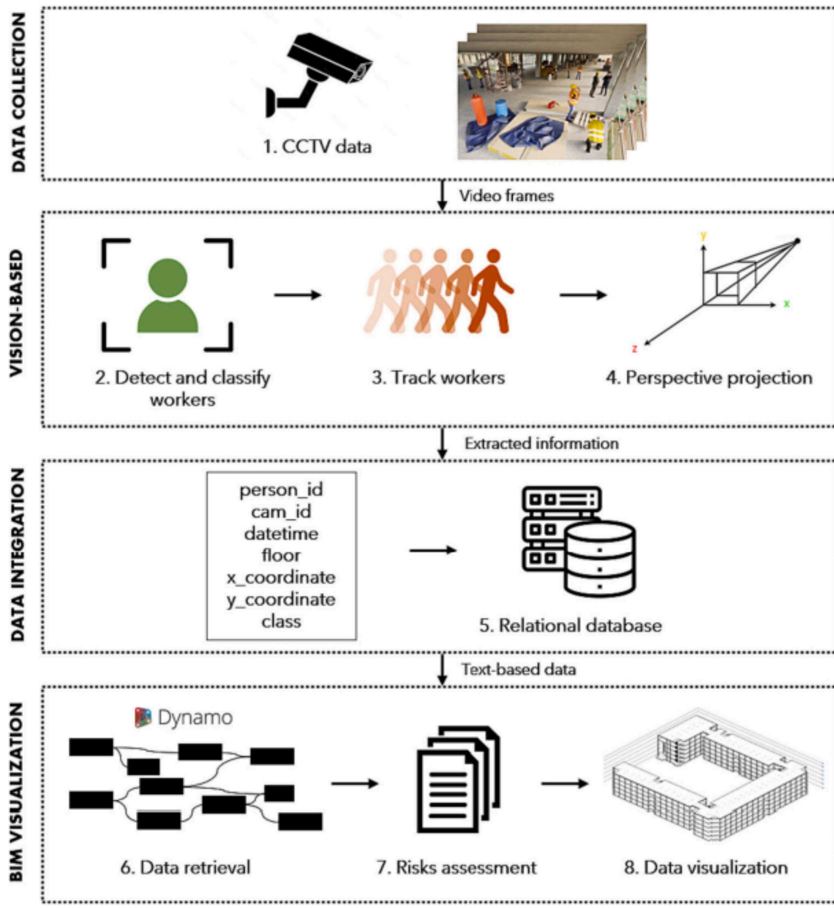


Figure 17. BIM framework and computer vision data integration for safety facility management system proposed by Kulinan et.al (2024)

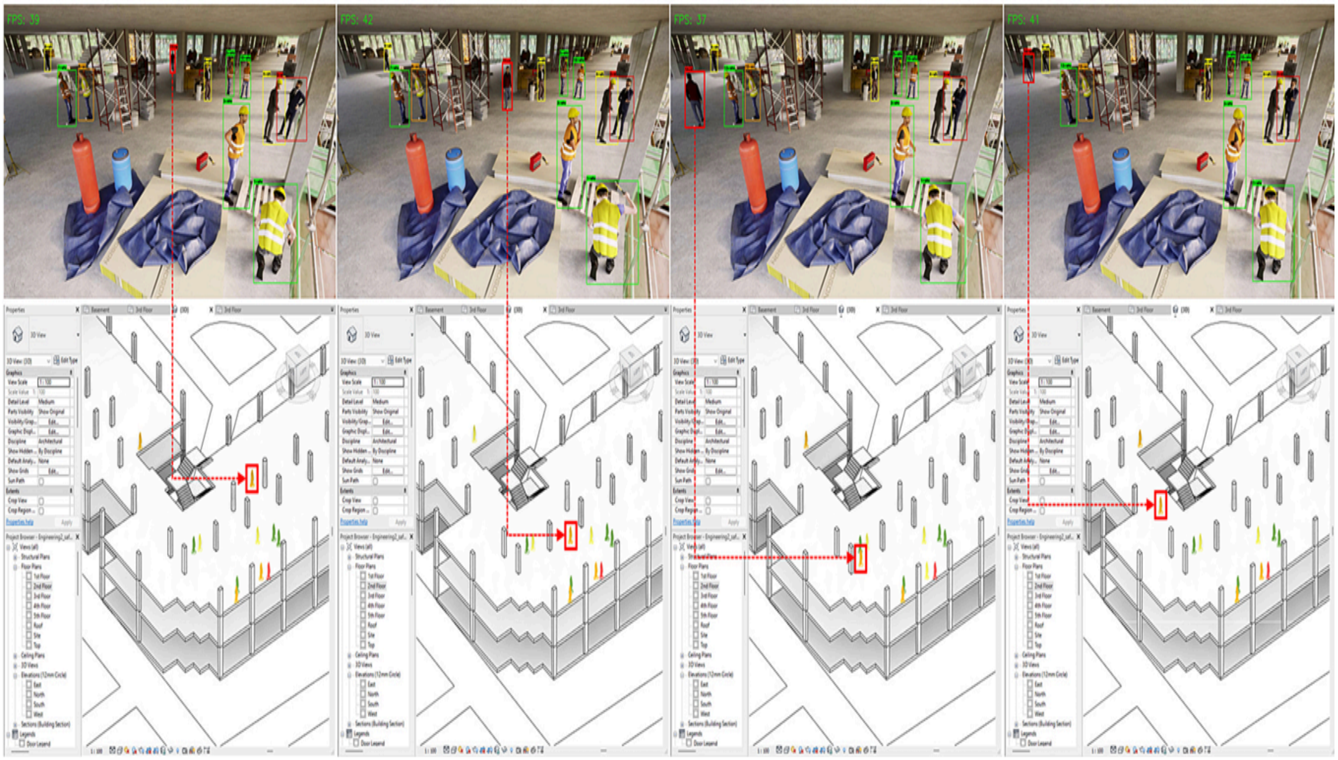


Figure 18. Results of testing compared to CCTV record and BIM version of the building

The system's risk assessment functionality provided significant support for safety managers. Workers were assigned risk levels based on their locations and PPE compliance, with these assessments visually represented in the BIM model through color codes. This visualization enabled managers to promptly evaluate and prioritize safety interventions. By integrating real-time and historical data, the BIM model facilitated a comprehensive approach to risk assessment, ensuring adherence to safety standards throughout construction activities (Kulinan et al., 2024).

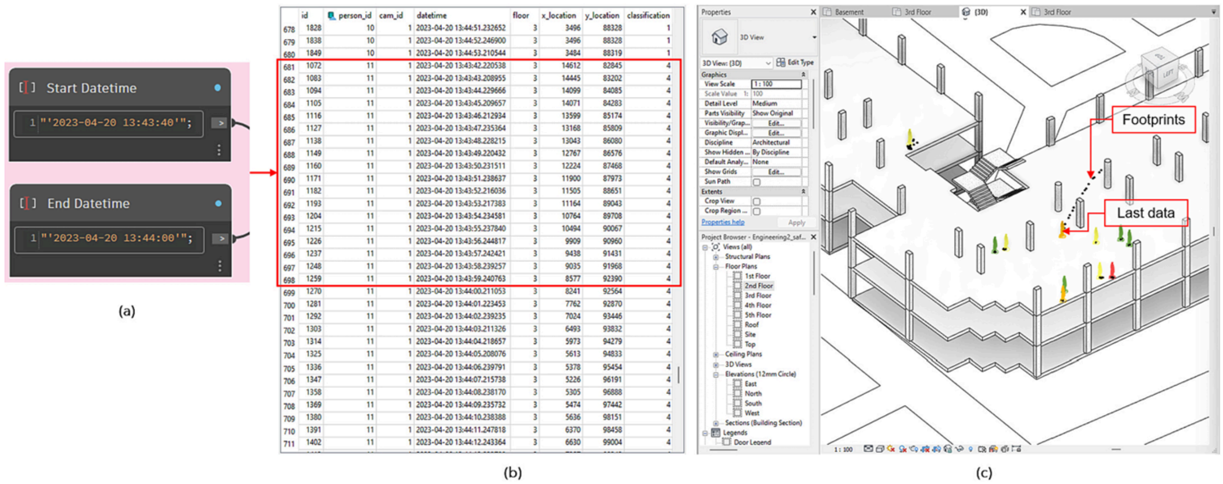


Figure 19. Historical data results with safety safety monitoring: (a) The time interval (b) RDBMS data (c) Visualization in BIM

2.7.Machine Learning for Accident Prediction in Construction Safety

Liu and Tian (2019) present an innovative method for evaluating and predicting construction safety by integrating distributed machine learning with extension cloud theory, creating an early warning system for construction accidents. The approach used by Liu and Tian provides a valuable foundation for developing models to analyze construction accident data and enhance site safety. The proposed system leverages diverse data sources, including worker behavior and equipment conditions, to identify potential safety risks early and reduce the likelihood of accidents.

The paper emphasizes human and equipment-related factors, enhancing the model's ability to pinpoint critical areas that could lead to accidents. For instance, human factors focus on adherence to safety protocols, participation in training programs, and fostering a strong safety culture. Collecting detailed data on how workers comply with rules and engage in safety initiatives allows for a more accurate assessment of human risk factors. Similarly, the equipment and materials category ensures that machinery is in good condition and that workers are equipped with appropriate protective gear and tools, further supporting site safety.

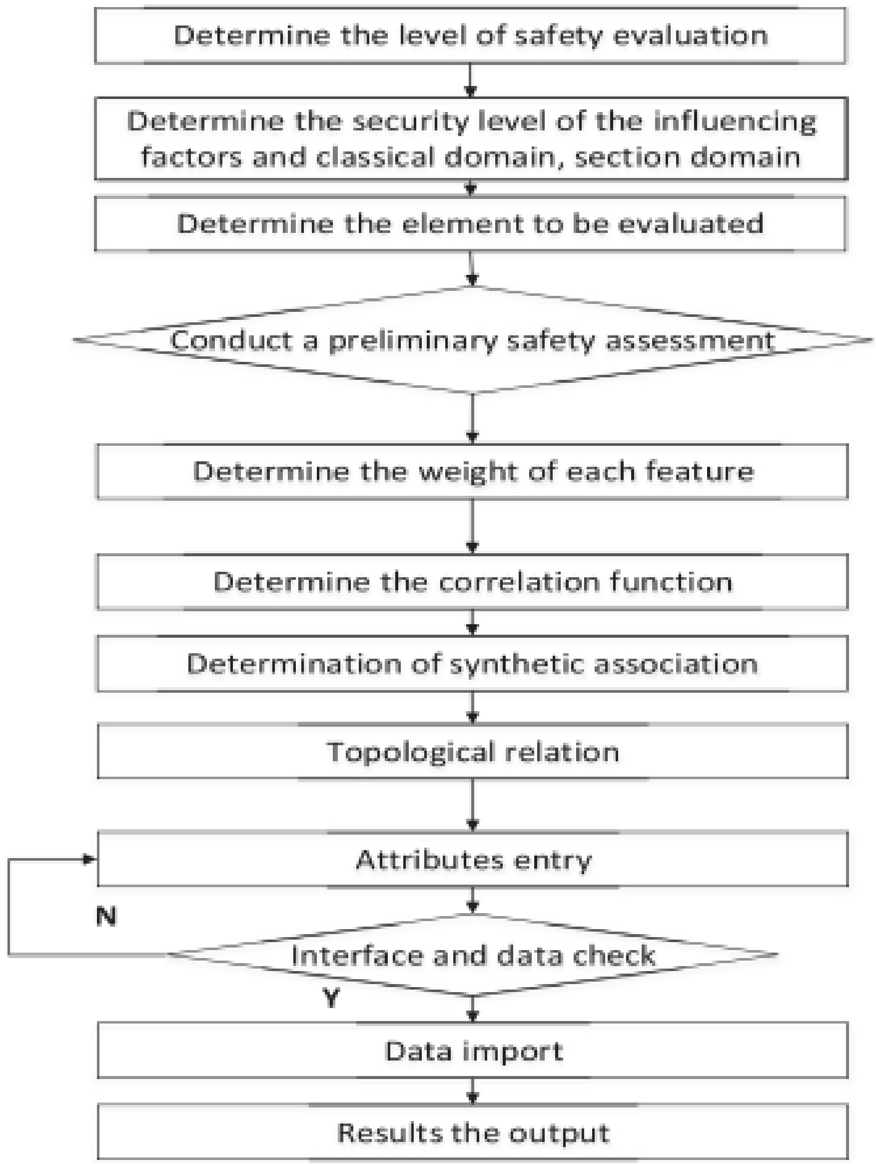


Figure 20. Safety management assessment and early warning mechanism grounded in extension cloud theory

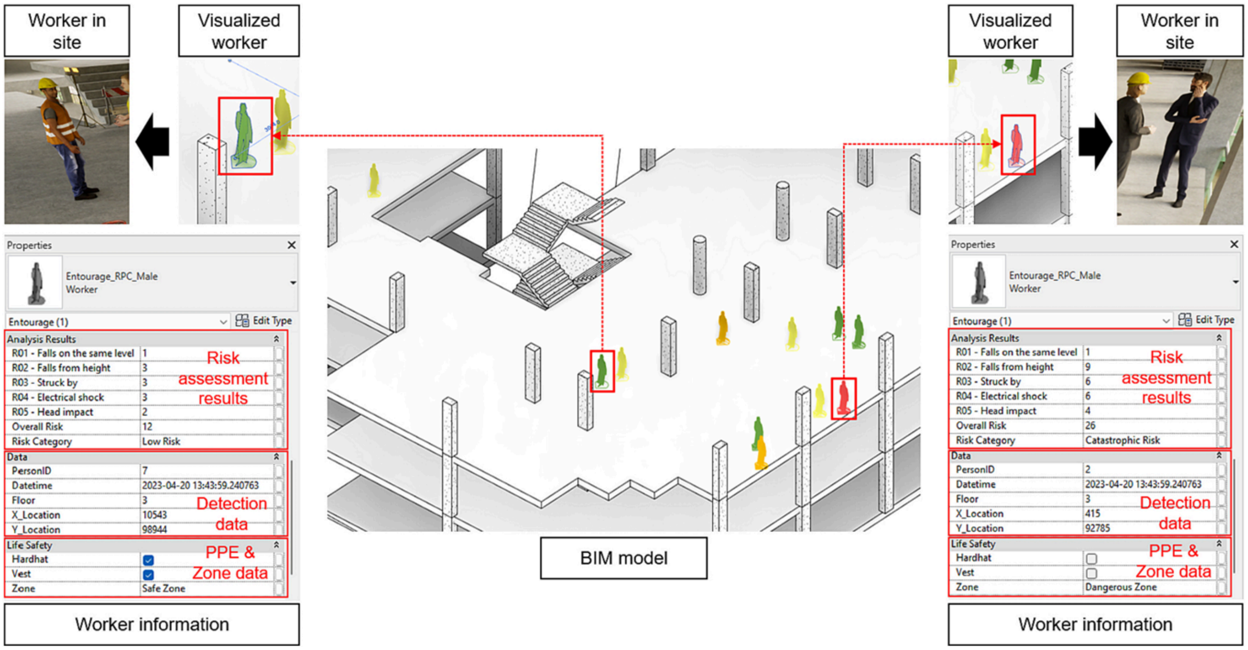


Figure 21. Data of workers being presented in a BIM model with all the family parameters

This model shown above creates the model of workers with their basic information stored in these models. These workers are created as a Revit family with the data that are presented as R01 to R05 with different characteristic features.

2.8. Synthesis of Literature Review

The table below presents the six measures with detailed descriptions, and summarizes their objectives, methods and findings. The main focus of these papers concerns the development of new BIM-based systems aimed at early risk identification in the construction process

Table 3

Synthesis of Literature Review

Source (References)	Purpose	Methods	Results
Wetzel, E. M., and Thabet, W. Y. (2015).	The detection, classification, transmission, and dissemination of safety-related	Built one data storage system aiming to establish an extensive, task-specific safety plan. The author used a	Categorized the safety inputs by collecting a variety of data into one data storage system using software programs and

	information to facility management employees.	quantitative analysis called a Six Sigma methodological approach.	research techniques.
Belsky, M., Sacks, R., and Brilakis, I. (2016).	A novel methodology aimed at enhancing an IFC exchange file by integrating meaningful concepts derived from both explicit and implicit information inherent in the building model.	A trial software was used to test this method, which includes a rule-processing engine, allowing for the creation of customized sets of inference rules for different areas.	Tests conducted with prototype software revealed that the techniques employed by an author can verify the layout of building components in the exported file.
Fargnoli, M., and Lombardi, M. (2020).	A thorough analysis of research articles that have emerged in the literature during the past ten years was conducted.	The literature review was done using the PRISMA guidelines. A total of 8 methods have been considered in this paper as the scope of research focused on the publications spanning from 2011 to 2019.	The findings indicated that the most effective research approaches could include knowledge-driven solutions, using BIM to enhance safety in design, diverse applications of BIM, and dynamic visualization with feedback.
Cheng, M., Chiu, K., Hsieh, Y., Yang, I.., Chou, J., and Wu, Y. (2017).	To create and put a comprehensive integrated fire prevention system to effectively avert fire	Using Building Information Modeling (BIM) to create an Intelligent Fire	The authors offered a BIM-based system to create a three-dimensional (3D)

	disasters and ensure the proper safeguarding of both lives and property	Prevention and Disaster Relief System based on BIM. The elements of this system construct an interactive and intelligent framework for fire disaster prevention, offering real-time, 3D-visualized information related to fires.	visualization to aid in evaluating and strategizing for fire safety. At last, it enhances the overall safety of buildings and bolsters their capacity to respond to disasters effectively.
Goh, Y., and Chua, D. (2010).	This research mainly focuses on using case-based reasoning (CBR) to identify safety hazards in construction. The aim is to improve the efficiency and precision of identifying new hazards by capitalizing on the wealth of historical knowledge contained within prior records of hazard identification and incidents.	The authors use the CBR methodology, where the system will retrieve the most pertinent hazard identification framework and a collection of incident cases. This retrieval process aids in streamlining the hazard identification process.	The authors developed a new CBR methodology that harnesses historical incident records and prior hazard identifications to streamline and support the identification of new hazards.
Hossain, M., Abbott, L., Chua, H., Nguyen, Q., and Goh, Y. (2018).	To develop a DfS rule-based library filled with knowledge to assist	The authors made use of the DfS knowledge library and implemented	The authors discovered that a significant number of the risks could have

	designers in identifying the risks before and during the construction phases of the life cycle of a building.	an intelligent risk assessment system integrated with BIM to aid designers in pinpointing risks associated with their design elements, including the necessary design characteristics. Additionally, a risk tracking system has been established within the BIM platform to keep tabs on any remaining risks.	been prevented or removed by using the DfS knowledge library and the intelligent risk review system at the beginning of the design phase. Consequently, employing these tools early in the project could prevent unforeseen delays or expensive design alterations later on, thus mitigating potential risks.

Note. This table demonstrates the six research papers with a summary of the purpose, methods, and results sections. The papers are mostly focused on the topic of developing a new BIM-based framework for the early detection of hazards during construction.

**Note.* The full references for this table are included in the References section.

Paper	Employer size	Sub-sector	Agency group	Age	Gender	Hours worked/ week	Employment type	Month	Day	Accident mechanism	Accident nature	Method/s
(Koc et al., 2021)		X								X	X	DT
(Sarkar et al., 2020)								X	X	X	X	SVM/ANN
(Choi et al., 2020)	X	X		X	X				X			DT, LR, RF
(Birhane et al., 2020)				X								Cause and effect
(Zhang and Hassan, 2019)		X	X	X	X			X	X			Multivariate analysis
(Kang and Ryu, 2019)	X		X	X			X			X	X	RF
(Winge et al., 2019)		X		X						X		Cause and effect risk assessment
(Ramdan et al., 2019)				X		X	X			X		Cramer's V test
(Wong et al., 2019)		X	X						X			LR
(Ramaswamy and Mosher, 2018)			X	X			X		X	X	X	Chi-sq
(Khashaba et al., 2018)			X	X						X	X	Case control study
(Guo et al., 2018)	X			X	X							Multi group factor analysis
(Winge and Albrechtsen, 2018)		X		X	X					X		Descriptive epidemiology
(Sharwood et al., 2018)		X	X	X	X			X		X	X	Descriptive statistics
(Chen et al., 2017)	X			X	X	X				X		CART
(Khodabandeh et al., 2016)				X	X		X			X	X	Pearson test & Kruskal-Wallis
(Soltanzadeh et al., 2016)	X	X		X								Chi-sq
(Hosseini et al., 2015)	X			X				X				Data visualization report
(Alizadeh et al., 2015)				X								BN
(Suárez-Cebador et al., 2014)		X	X	X						X	X	Chi-sq
(Lipscomb et al., 2014)		X		X								Descriptive statistics
(Dumrak et al., 2013)	X	X		X	X			X	X	X	X	Descriptive statistics
(Cheng et al., 2012)	X	X		X	X		X			X		CART
(Cheng et al., 2010)	X	X	X	X	X					X		Characteristic analysis
(Barss et al., 2009)			X	X						X		Injury severity score analysis

Notes: **CART** = Classification and regression tree, **RF** = Random Forest, **LR** = Logistic regression, **SVN** = Support vector machine, **ANN** = Artificial neural network, **BN** = Bayesian network, **DT** = Decision tree.

Figure 22. The summary of literature review on ML-based approach for construction safety

The Figure 22 depicts the classification of papers by different authors based on the methods used in analyzing the obtained data regarding various types of injuries in construction sector. There are 11 main variables which are picked as primary classification for analyzing the data. Using these 11 variables each of the authors used different methods and libraries to predict the accidents that might happen in the future.

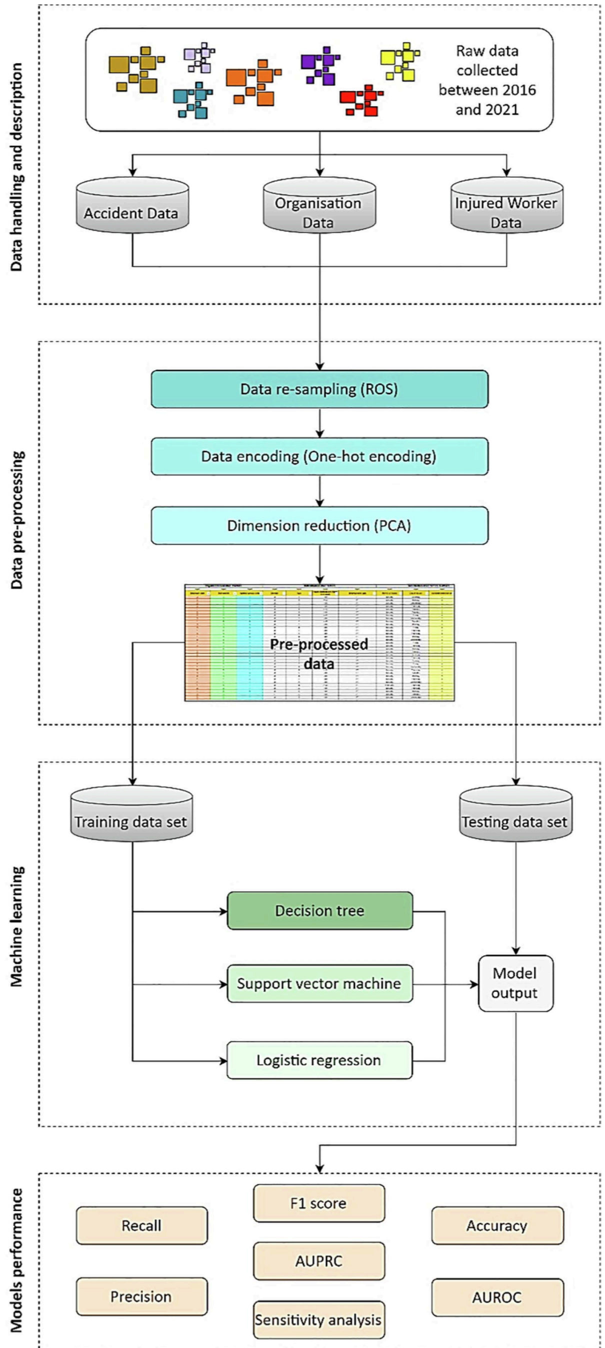


Figure 23. Data analysis workflow

Figure 23 shows the workflow for the data analysis in machine learning to use it in construction sector. First step is collecting the raw data for the last five years to further analyze it using machine learning. Second step is the pre-processing stage where there is data re-sampling, encoding and reduction. Then the data set is created to further use the machine learning methods to improve the data analysis of the collected data. Then using various methods the performance of the machine learning method is tested and analyzed.

First indicators	Second indicators	Third indicators	Evaluation standard
Construction safety evaluation	Human factor RL	Worker safety ideological quality and team spirit knife RL1	Score
		The workers obey the rules and regulations and fulfil their duties RL2	Score
		Active participation rate of workers in safety activities RL3	Ratio
		The psychological quality of workers' safety is RL4	Score
		The literacy of workers RL5	Score
	Factor of substance BL	Safety culture quality and safety technology level of project management BL1	Score
		Safety condition of construction machinery and equipment TF construction materials qualified rate knife BL2	Ratio
		Allocation rate knives for safety protection supplies BL3	Ratio
		Spare rate knives for safety inspection and testing tools BL4	Ratio
		Safety warning mark and slogan setting ratio TF BL5	Ratio
	Environmental factor FL	Engineering technical environment (including geology, hydrology, meteorology, etc.) FL1	Score
		Engineering operation environment (operation area size protection equipment, ventilation lighting, communication, etc.) FL2	Score
		The surrounding environment of the project (the underground pipeline near the project, building structures, etc.)EF FL3	Score
	Management factor SL	The security civilization fund is invested SL1	Score
		Safe education training rate SL2	Ratio
		Safety inspection ratio Yin SL3	Ratio
		Construction organization design SL4	Score
		Special construction plans SL5	Score
		Security technology disclosure SL6	Score
		Hazard identification and control SL7	Score

Figure 24. Comprehensive assessment index framework for construction safety

Chapter 3 - Methodology

3.1. Literature review following PRISMA guidelines and VOSViewer visualization

The concept of DfS is found to be very effective as a preventive measure for construction, operation, and maintenance, and it has been receiving growing attention in recent years (Gambatese et al., 2005). Nevertheless, the DfS implementation is still in its early development stages. Most of the efforts have been made to prevent construction-related hazards, and more needs to be done to manage FM-related hazards through proper design consideration (Hossain et al., 2018). This study employs the Design for Safety (DfS) concept to integrate safety knowledge into Building Information Modeling (BIM) to assess maintenance risks in FM.

As recommended by the PRISMA guidelines, a systematic literature review was conducted with the following steps as schematized in Figure 25(Moher et al., 2010):

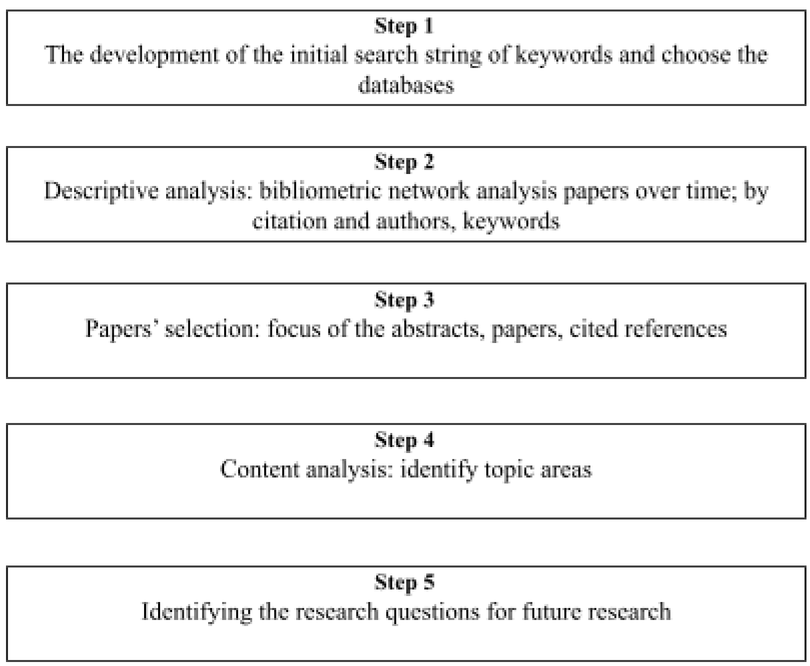
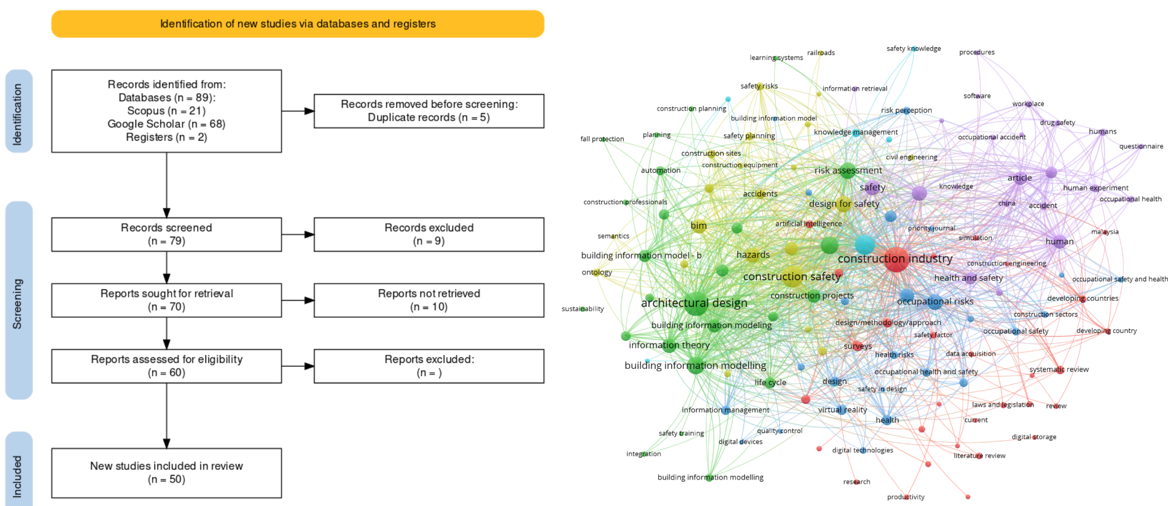


Figure 25. Flow chart describing the algorithm for PRISMA systematic review

Figure 25 depicts the flow chart with five steps for the Literature review using the PRISMA systematic review and each step was carried out according to the outlined criteria.

- Scope Definition: Academic papers focusing on using the BIM in the initial phases of construction to ensure safe building management.
- Databases: Two databases which are Scopus and Web of Science were chosen for their huge recognition as inclusive archives of peer-reviewed research.

- Screening Criteria: The search aimed at identifying journal articles published in English starting from 2013. For both Scopus and Web of Science, the search string was "dfs-based AND bim AND for AND safe AND facility AND management."
- Eligibility Assessment: Abstract analysis was conducted to assess the appropriateness of articles for inclusion, considering the scope of the review. Following this, a careful examination of the full texts of selected articles confirmed their relevance to the research.
- Classification: The initial classification of chosen studies took into account publication characteristics like publication year, primary author's country affiliation, and the journal. This process offered insight into research patterns concerning the safety applications of BIM over the last decade.
- Categorization: Selected studies were further examined, considering their nature, whether empirical or conceptual, using methodologies akin to those proposed in prior research.



(a) (b)

Figure 26. (a) Flow chart including the PRISMA systematic review for Literature Review; (b) Visualizing a Literature Review using VOSViewer

VOSviewer is a software application designed to construct and visualize bibliometric networks, which pertain to the quantitative examination of academic literature encompassing elements like citations, co-authorship, and keyword co-occurrence. Frequently utilized in scientometrics, VOSviewer aids in the analysis and graphical representation of patterns found in extensive collections of scientific literature. Figure 26 illustrates the visual representation of bibliometric networks from the PRISMA literature review method.

3.2. Design for Safety-Based BIM Framework

In order to improve safety knowledge through semantic improvement of Building Information Modeling (BIM) and enable the analysis of maintenance risks in Facility Management (FM), this project employs the Design for Safety (DfS) paradigm. The BIM model serves as the focal point of the system architecture that the study proposal describes, as seen in Figure 4. The counseled system has two Safety Knowledge libraries, which provide flexibility for everyday preservation, together with additions, modifications, and removals. These libraries feature as an in depth safety information useful resource through effortlessly integrating with any BIM model.

The device includes two protection expertise libraries, one focusing on design flaws and the alternative on production/set up flaws. The waft chart for acquiring facts and protection data is shown in Figure nine. First, a radical exam of the literature touching on protection studies and pointers will expand a foundational body of knowledge. Professionals in FM will then examine and upload to this set to make it extra in step with Kazakhstan's safety guidelines. The safety troubles may be investigated in element to look how they relate to layout and/or production, and whether or not correct layout issues, production, or set up may additionally enhance safety.

Acquisition of Design for Safety expertise and identification of protection protection issues due to creation deficiencies can be facilitated via diverse approach, inclusive of consulting relevant studies literature, case studies, accident records, protection reviews, awareness institution discussions, and semi-based interviews with specialists and practitioners.While no on-website online data collection or place measurements are presently planned, those sports may be performed if deemed vital.A taxonomy encompassing this knowledge will then be evolved and validated via relevant specialists. For example, maintenance work is probably difficult if the slope of a pitched roof exceeds 20°, posing risks together with an "inconvenient working platform" and "fall from a top".This safety issue is design-related and can be improved by designing the pitched roof with a slope of 20° or less, which can be established as a design requirement forming the basis of the DfS rule. If the pitched roof fails to meet the DfS rule (i.e., slope > 20°), a maintenance hazard would be identified, and an alternative mitigation suggestion could include an "access route to the pitched roof including a working platform".

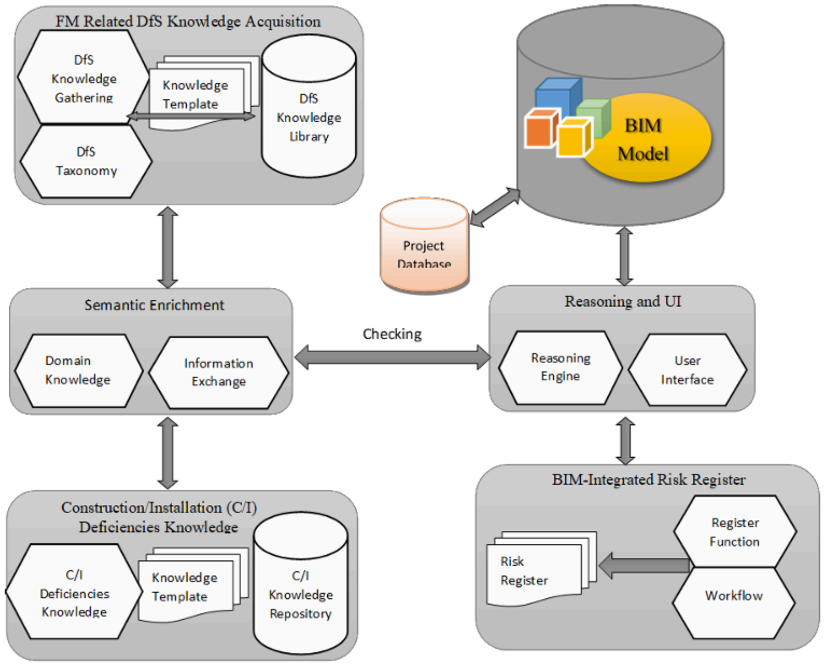


Figure 27. BIM-Integrated Risk Review System Architecture for FM

Similarly, "falling from the roof during maintenance" is a typical risk associated with flat/sloped roofs that may be reduced by putting "safety hooks and anchorage points for safety lines" during construction. Moreover, a number of risk variables that are articulated with logical AND/OR interactions are frequently involved in safety difficulties. Accordingly, the knowledge will be stored in two knowledge libraries for automatic checking during design and construction using the BIM model.

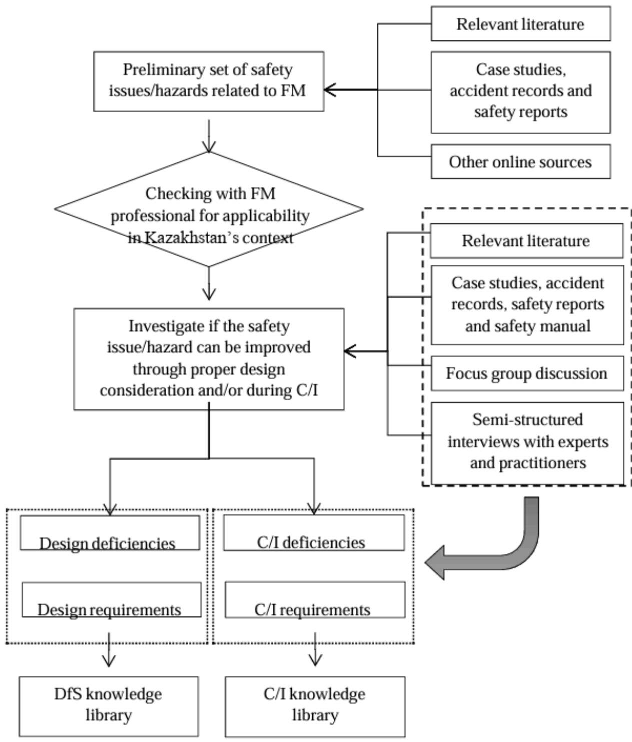


Figure 28. Data and Knowledge Acquisition Flow Chart

3.3. Keeping Records of Accident Cases

After a detailed consideration of these cases, the obtained data was further analysed by various criterias. Different risk drivers integrated with the building information modelling could automatize the preventive measure by facilitating keeping safety on cite. After a thorough analysis, among 363 cases almost half of the cases are directly connected to the concept of DfS. By using various risk drivers that are environmental parameters that would impact the accident risk which will be violated or will not be violated. Figure below represents the zoning of the construction site in the BIM model with a green area being a safe zone while red area being a dangerous zone for workers.

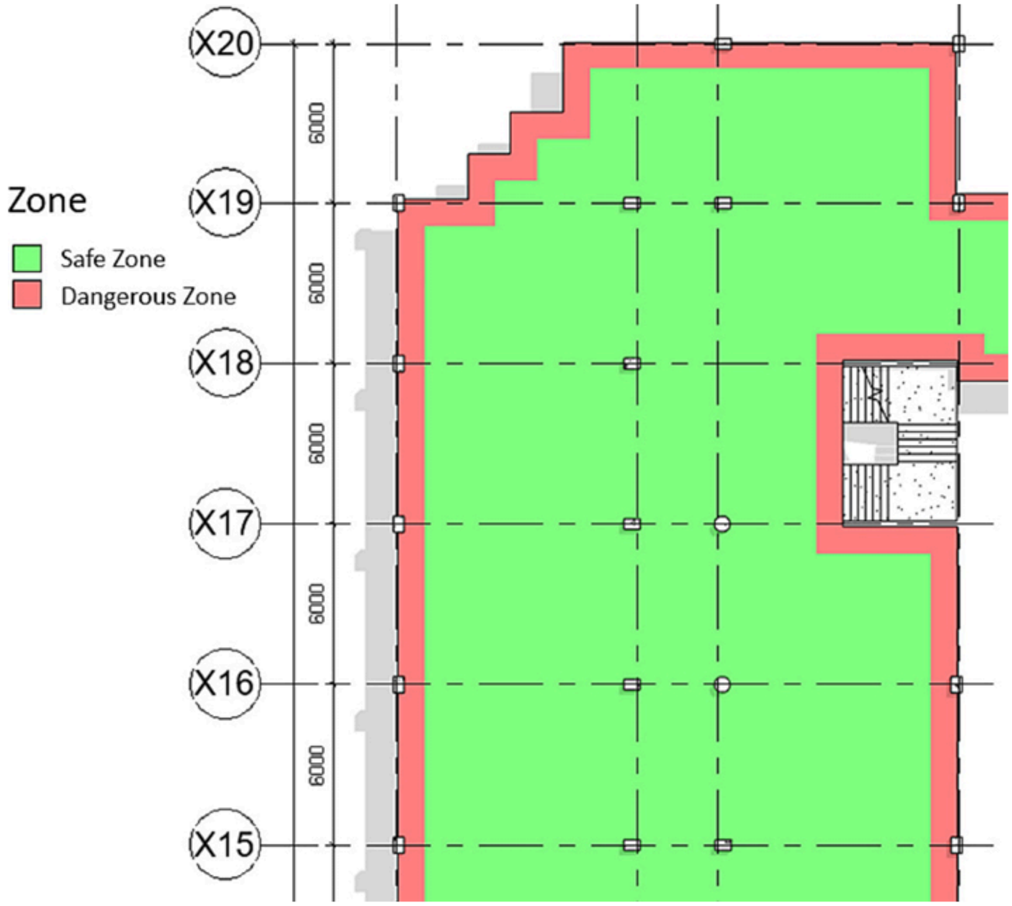


Figure 29. BIM model with the zoning of construction site

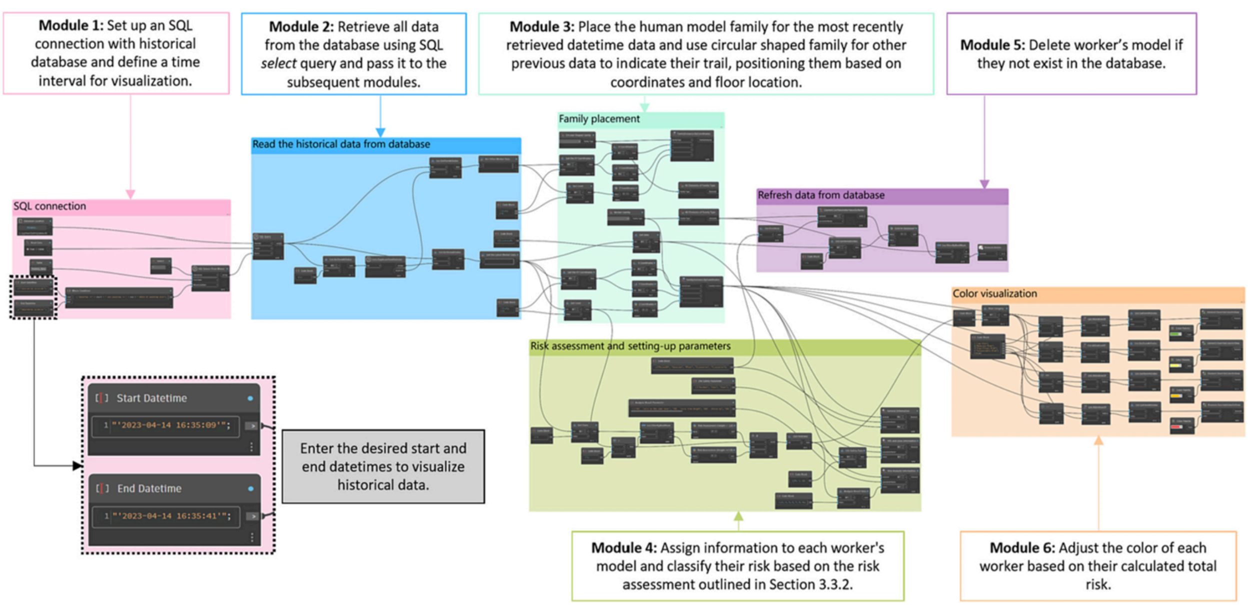


Figure 30. Algorithm created as Dynamo code to analyze the historical data

The historical data will be analyzed by using the algorithm that was developed in Dynamo as a visual code boxes. This dynamo code consists of six different modules which are connection with database using SQL connection, data retrieval using SQL query, placing the human model family, assigning an information to each of the workers, selecting models based on their existence on the database and adjusting each model based on the color of the risks.

To discuss each step in detail, the first step includes in itself the creation of SQL connection to the database with workers' information. The second step is to retrieve all the information from the database with the use of features of SQL to further go to next steps. Third step includes placing the human model family designed on Revit into their respective positions and floor locations, taking into consideration the live location taken from CCTV. Fourth step is assigning data to each of the workers' models and also to classify risk factors based on the selected data. Fifth step is to select only those human models that are present in the database analyzed using SQL query and deleting those human models that do not match the retrieved data model. The final step is to classify each workers' model based on their respective risk colours.

Risk (R) = L × S		Severity (S)		
		Negligible -1	Moderate – 2	Critical - 3
Likelihood (L)	Frequent - 3	3	6	9
	Occasional - 2	2	4	6
	Rare - 1	1	2	3

Figure 31. Risk assessment matrix

Figure 31 clearly shows the risk degree by its severity and likelihood. For example. the accident with the most severity of score 3 has the most frequent likelihood, these two values are multiplied and its final value is 9.

Table 4

Risk level classification based on the information retrieved before

Risk code	Uncontrolled risk			Risk control measure	New code	Controlled risk		
	S	L	R			S	L	R
R01	1	1	1	No action needed	-	1	1	1
R02	3	3	9	Workers should not work or stay in dangerous zone	C02	3	1	3
R03	3	2	6	Workers should always wear high-visibility vest	C03	3	1	3
R04	2	3	6	Workers should always wear hardhat	C04	1	3	3
R05	2	2	4	Workers should always wear hardhat	C05	1	2	2

Table 4 shows different risk control measures for the initial risk codes and then these values are further modified to new codes after going through the measures for each of the cases.

Chapter 4 - Results and Discussion

4.1. DfS Knowledge Library Creation

As evidenced by the preceding discussion mentioned in the literature by many authors, designers encounter challenges primarily in identifying the hazards and risks associated with their design elements across various stages of work. Specifically, designers may lack awareness of the conditions and constraints that could pose risks by a design element. For example, if a precast beam's length exceeds a specific limit or if lifting points are not sufficiently provided, it may provide concerns related to shipping, breaking, or falling objects. According to Hossain et al. (2018), designers frequently fail to consider the necessity of providing lifting points and certain beam lengths for safe handling, shipping, and installation.

To assist designers in integrating Design for Safety (DfS) knowledge, it is imperative to ensure that rules about length and openings are meticulously checked in libraries according to specified requirements.

Therefore, the implementation of a checking system becomes indispensable, incorporating safety rules within a DfS knowledge library. Establishing these safety rules, however, requires specialized information on the grounds that extraordinary design functions can also offer awesome risks beneath diverse settings and barriers. Furthermore, depending on sure occasions and barriers, distinct factors of the greatest important design may want to want for use to lessen risks (Hossain et al., 2018). Thus, with a purpose to seize DfS expertise in an prepared way, a framework is vital.

4.2. Integration of DfS Knowledge into BIM Platform

The DfS knowledge repository acts as a resource for designers to evaluate their designs, identifying and proactively addressing potential risks during the design phase. Given the pivotal role of BIM in facility management, it's imperative to integrate safety considerations into the BIM model to enhance visualization and resolution capabilities. Consequently, a BIM-integrated intelligent risk assessment system is devised, capitalizing on the DfS rule-based knowledge repository (Hossain et al., 2018). This system comprises three fundamental elements:

1. A DfS knowledge repository containing guidelines for design-related hazards.

2. A reasoning engine responsible for interpreting safety guidelines for intelligent design assessment using BIM-compatible building models.
3. A BIM-integrated risk management system, streamlining the handling and oversight of identified safety concerns.

The intelligent DfS assessment system functions through a specialized language tailored for DfS analysis, scrutinizing BIM-compliant building models for potential design hazards. Central to this system is the Reasoning Engine, which interprets BIM-compliant digital models in the IFC format and employs a suite of safety evaluation algorithms (Hossain et al., 2018). The engine cross-references the physical parameters of the building within the BIM model against established DfS guidelines, generating a roster of identified design hazards. These hazards are subsequently visualized and annotated within the BIM-compliant 3D model and logged within a Risk Management System.

This research project will adopt some parts of the methodologies utilized by Hossain et al. (2018), as their proposed approach closely aligns with the objectives of this study. The incorporation of DfS knowledge within the BIM infrastructure, along with the development of an intelligent risk assessment system, mirrors the framework established by Hossain and colleagues. However, while their study focused on a broader scope, this research will specifically target the Republic of Kazakhstan for data collection and analysis. By applying similar methodologies tailored to the context of Kazakhstan, this study aims to contribute valuable insights into enhancing safety practices within the country's construction and facility management sectors.

4.3. Clash Detection Analysis and Model Checking using Tekla Structures

The BIM software device mostly have a big feature in it called "clash detection evaluation" which is used to determine whether or not there is a possibility of a collision between various architectural additives, structural parts, and MEP systems. In the case that those collisions aren't resolved, they might create ability protection troubles in the course of creation and afterward. BIM generation makes it possible for creation specialists, which include architects, engineers, and other production professionals, to paintings collectively on warfare detection analyses. Clashes may be spotted early within the design section through realistically modeling the development method and reading how special constructing components engage with each other.

This makes it possible to discover a strategy to the problem more fast. Alterations to the design had been advised to assure that the various constructing additives can coexist peacefully.

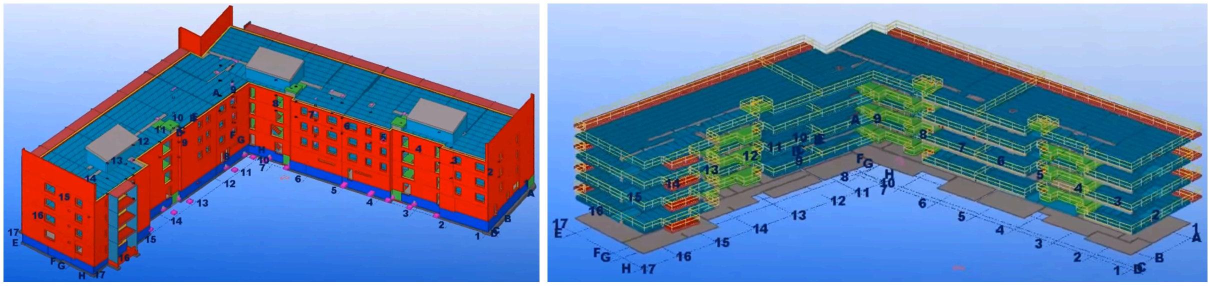


Figure 32. Structure designed in Tekla and check for slab edge, covers, guardrails

The Figure 32 shows the building designed in Tekla Structures that include dangerous areas for construction workers. The BIM software Tekla Structures has a clash detection tool which can check the model family of the person with objects after the risks are identified.

The purpose is to improve overall safety in the construction industry through the evaluation of the safety of building design using clash detection analysis. Its purpose is to lessen the likelihood of any potential dangers and to contribute to the establishment of a safe and risk-free environment within the structure. The 3D model designed in Tekla Structures includes covers and guardrails designed according to OSHA regulations.

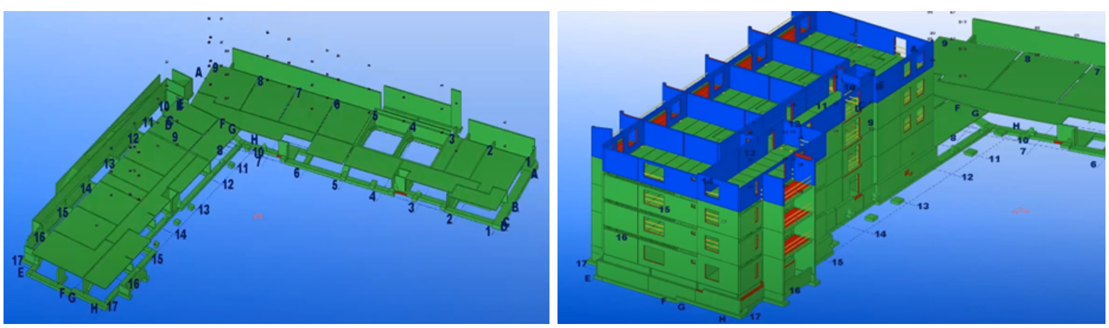


Figure 33. Visualization of a project status during the whole construction process considering the safety measures

Figure 33 depicts a project status during the whole construction process considering the safety measures.

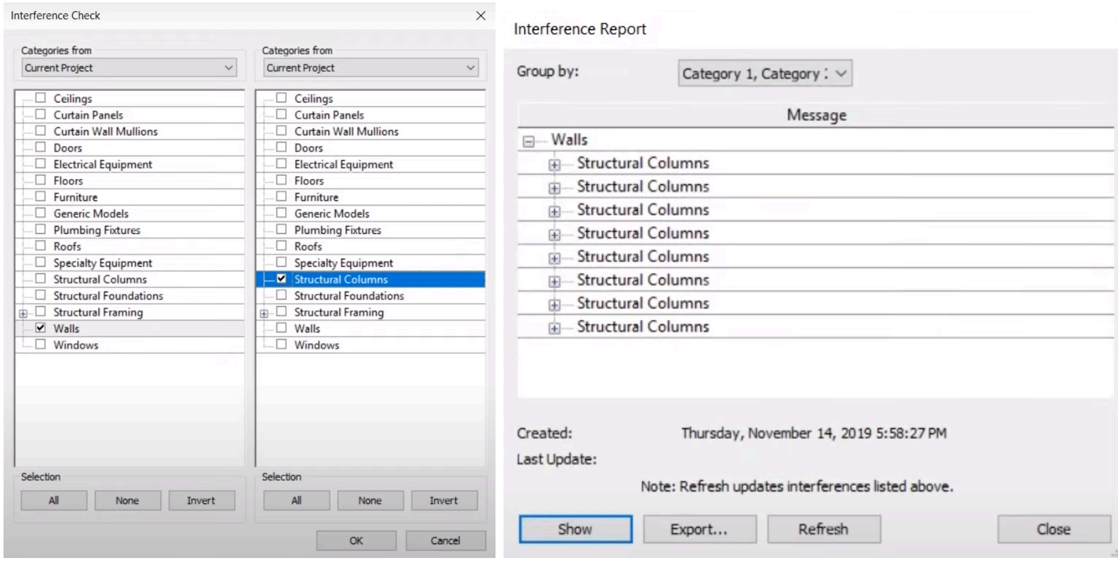
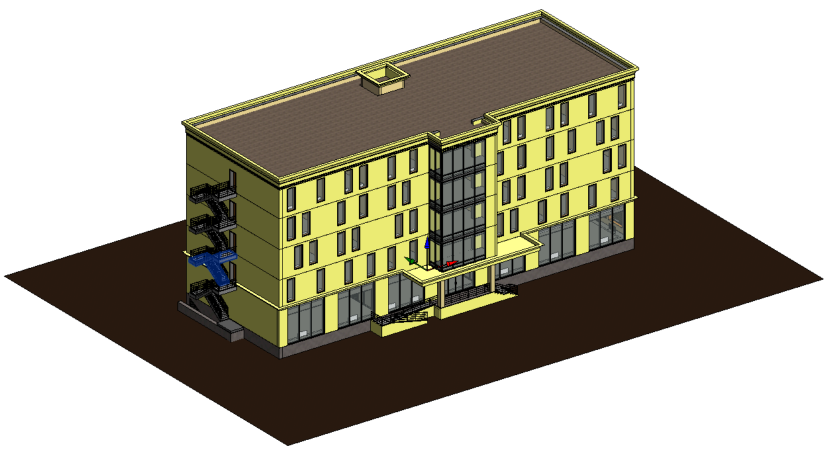
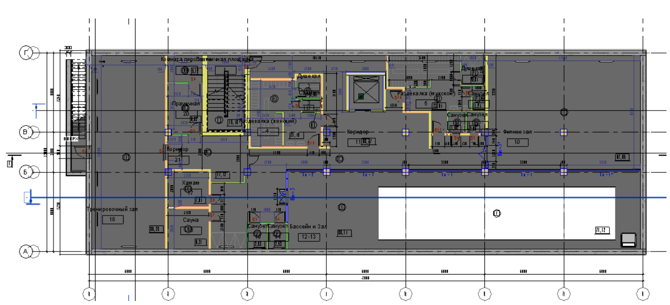


Figure 34. Clash detection and interference report on a 3D model of the business center



(a)



(b) ©

Figure 35. (a) 3D model of business center for risk management on Autodesk Revit (b) Side view of business center for risk management on Autodesk Revit (c) Floor plan of a foundation plan of the business center for risk management on Autodesk Revit

The Autodesk Revit software was used to make a detailed 3D model, aiming to check for possible risks. The main goal was to create a clear picture of the project or building to spot and assess any dangers that might potentially arise. To begin with, Autodesk Revit software is used, which is very convenient for architectural design and modeling, the building of a business center was created. Then, every detail of the project was carefully included in the 3D model, making sure nothing was left out.

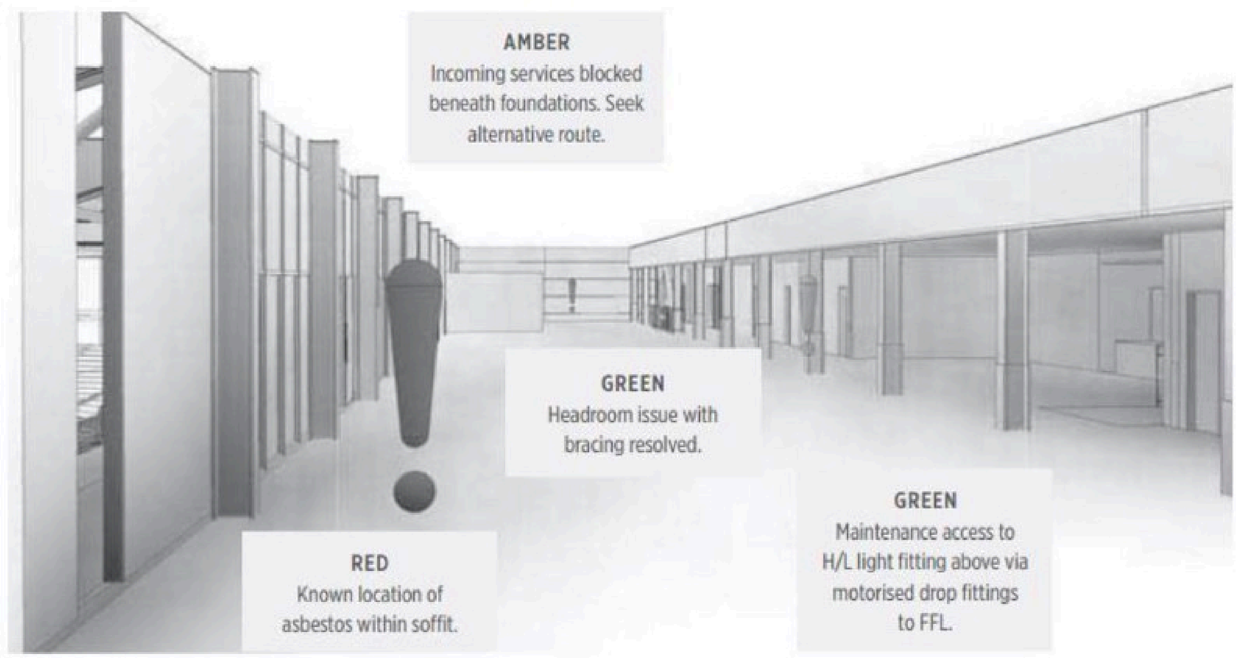


Figure 36. Visualization of identified possible risks

The next step that should be done is classifying the identified possible risks by assigning colors to them and defining them in the characteristics of the BIM model where DfS knowledge data will be stored.

4.4. The use of ML for construction safety

```
import pandas as pd
from sklearn.model_selection import train_test_split
from sklearn.ensemble import RandomForestClassifier
from sklearn.metrics import accuracy_score, classification_report

# Load dataset (replace 'file_path' with actual data path)
data = pd.read_csv('construction_accident_data.csv')

# Data preprocessing
features = ['age', 'gender', 'accident_mechanism', 'employment_type', 'hours_worked']
target = 'injury_type'

# Convert categorical variables to numeric
data = pd.get_dummies(data, columns=features)

# Split data into training and testing sets
X = data.drop(columns=[target])
y = data[target]
X_train, X_test, y_train, y_test = train_test_split(X, y, test_size=0.2, random_state=42)

# Train Random Forest model
rf_model = RandomForestClassifier(n_estimators=100, random_state=42)
rf_model.fit(X_train, y_train)

# Make predictions
y_pred = rf_model.predict(X_test)

# Evaluate model
print("Accuracy:", accuracy_score(y_test, y_pred))
print("Classification Report:\n", classification_report(y_test, y_pred))

# Feature importance
feature_importances = pd.DataFrame(rf_model.feature_importances_,
                                   index=X_train.columns,
                                   columns=['Importance']).sort_values(by='Importance', ascending=False)
print("Feature Importances:\n", feature_importances)
```

Figure 37. The application of Machine Learning (ML) to predict injury types in the construction industry using a Random Forest Classifier

The Python script depicted on Figure 37 shows the machine learning method that is used to predict different types of injuries in the construction industry, by providing a real practical way to make safety management better. The method used on the ML is a Random Forest Classifier which helps in changing safety practices from reacting to issues to actively preventing them. With predictive analytics, this script helps in understanding risk factors and improves decision-making regarding safety. The algorithm of this code is further depicted as a flowchart in Figure 38 where each step is clearly explained.

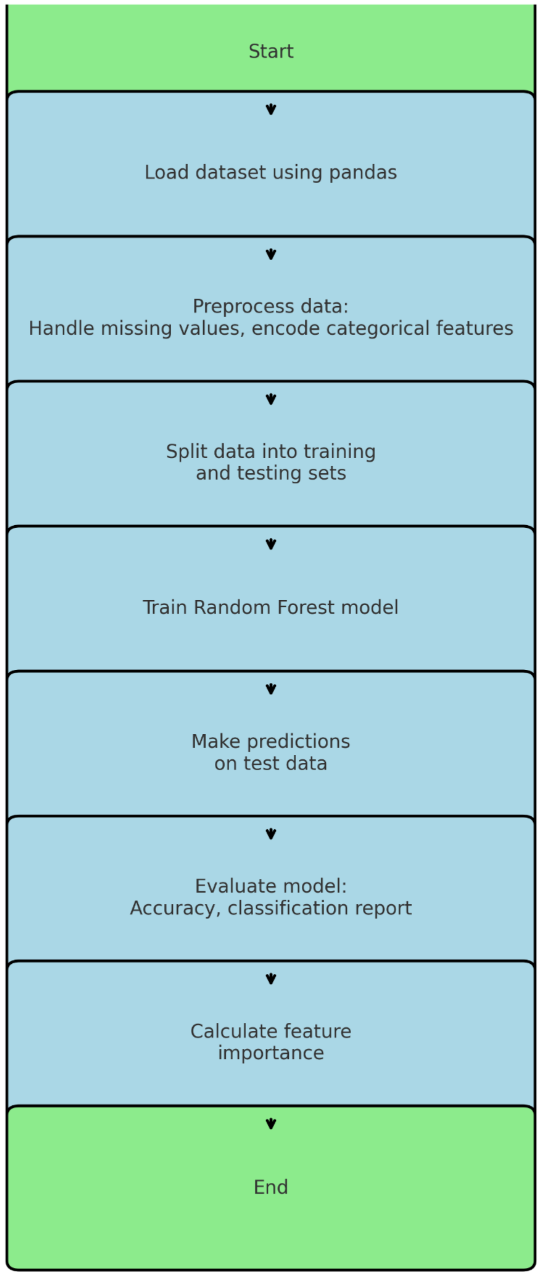


Figure 38. A flowchart describing the application of Machine Learning (ML) to predict injury types in the construction industry using a Random Forest Classifier

Figure 38 depicts a flowchart that explains the machine learning application to predict the types of injure using the historical data. First steps include loading the data into the model and preprocessing it by selecting the existent and non-existent data. After the first step goes the next step which includes dividing the data into different sets for training and testing. Then the data goes through the method of machine learning that is random forest model to train this method.

Table 5

A sample data used for the classification of different zones and human models

No.	person_id	cam_id	datetime	floor	x_location	y_location	category
1	16	1	2023-04-20 13:25:33.477941	3	30,976	97,425	4
2	13	1	2023-04-20 13:25:33.477941	3	10,542	98,981	1
3	12	1	2023-04-20 13:25:33.477941	3	10,265	97,980	3
4	10	1	2023-04-20 13:25:33.477941	3	3496	88,328	1
5	9	1	2023-04-20 13:25:33.477941	3	29,486	94,450	2
6	8	1	2023-04-20 13:25:33.477941	3	5780	90,526	2
7	5	1	2023-04-20 13:25:33.477941	3	4667	88,277	1
8	4	1	2023-04-20 13:25:33.477941	3	906	93,614	6
9	3	1	2023-04-20 13:25:33.477941	3	1497	97,782	1
10	2	1	2023-04-20 13:25:33.477941	3	272	92,703	8
11	1	1	2023-04-20 13:25:33.477941	3	339	98,818	5

Table 5 above consists of 11 different human information first stored using SQL with their respective coordinates and safety categories. These data are proposed to be taken from CCTV footages further being developed into the BIM, Revit model family that can store all the information stored in the columns of the table. These data can be used to check the equipment gear on the workers and to know the positions to warn about the most risky parts of the construction project.

Chapter 5 - Conclusions

5.1. Implications of the Research

This study can help in many ways. It can improve safety and efficiency by adding safety info to BIM. This makes a smart way to review risks and helps with safety and efficiency in building and facility management. This way can find and deal with safety issues early, which can save money and make better use of resources.

Also, this plan can work as a tool to help meet rules by handling safety needs through the project. By checking risks in facility management with BIM tools, groups can lower risks, stop accidents, and meet industry rules. This can also lower legal troubles and fines.

The study adds a lot to knowledge about construction safety, BIM, and facility management, and it offers new ways for the industry to use. If the plan is put in place well, then more groups may use BIM for safety, and this could change how safety is run in the world.
Main three conclusions of my thesis are (1) Integrating BIM with Design for Safety (DfS) enhances early detection of risks, improving safety in facility management (2) DfS-based safety library within BIM helps manage real-time safety risks, reducing accidents during maintenance (3) The proposed BIM framework is well-suited to Kazakhstan's facility management, with potential to significantly enhance safety standards. The achievement of these conclusions are further discussed.

5.2. Justification of Achieving the Objectives and Conclusions

In short, there is a huge progress in answering the initial research questions:
It was considered how Facility Management (FM) dangers and poor design/construction methods are linked. This gave useful information on how safety is managed in buildings. By studying existing research and methods, the groundwork was laid for understanding how design flaws and safety risks are connected in construction projects. After the literature review, it was concluded that the use of BIM itself cannot help to achieve the "design for safety", however the use of other technologies such as machine learning ,4D BIM and Digital Twin along with BIM facilitates the

progress of an entire construction project as according to the research it greatly reduces the number of incidents on site, without sacrifising on economy and time as it happens to be usual.

The initial plan was on creating a framework that uses the information to database to update the BIM model about the incident cases and using machine learning conduct a predictive analysis, which was influenced by previous studies, outlines a detailed framework for adding safety knowledge into Building Information Modeling (BIM) and assessing maintenance risks in FM. After reviewing lots of literature and planning our methods, important parts and steps for creating a smart risk review system that's kept in BIM and updated every time after being filled with the information from the real-time.

In the future, the focus will be on using and testing the new system, especially in Kazakhstan's construction and facility management fields. By using BIM tech and adding in more meaning, we aim to improve safety practices and lower risks faster. This move is a big step toward making workplaces safer and promoting a culture of preventing risks in the construction business.

5.3. Future Recommendations

While this study demonstrates the potential of integrating Design for Safety (DfS) principles with Building Information Modeling (BIM) to enhance safety in facility management, several areas need further investigation. The fast improving nature of digital construction technologies and the increasing complexity of facility operations present both challenges and opportunities for extending the current framework. Future research should aim to refine the interoperability between DfS-based design inputs and BIM platforms throughout a building's lifecycle, as well as explore more dynamic ways to incorporate real-time safety data and user feedback into facility management processes. Additionally, broader validation across diverse building types, stakeholder groups, and geographic contexts will be essential to generalizing and scaling the proposed approach. There are three main goals for the future research:

- Testing the BIM-Based Framework: Future studies will focus on implementing and testing the proposed BIM-based safety framework in real-world projects, particularly in Kazakhstan, to validate its effectiveness in reducing facility management risks.

- Expanding the DfS Knowledge Library: Research could explore expanding the safety knowledge library by incorporating more localized safety data, industry standards, and advanced technologies like AI for automated risk detection.
- Improving Semantic Enrichment: Further studies could investigate advanced methods for semantic enrichment of BIM models to enhance the precision and efficiency of safety evaluations during the design and maintenance phases

References

Alkaissy, M., Arashpour, M., Golafshani, E. M., Hosseini, M. R., Khanmohammadi, S., Bai, Y., & Feng, H. (2023). Enhancing construction safety: Machine learning-based classification of injury types. *Safety Science, 162*, 106102.

Aram, S. (2014). A knowledge-based system framework for semantic enrichment and automated detailed design in the AEC projects. PhD thesis, Georgia Institute of Technology, Atlanta, Georgia, United States.

Azhar, S. and Behringer, A. (2013). A BIM-based Approach for Communicating and Implementing a Construction Site Safety Plan [Paper presentation]. 49th ASC Annual International Conference Proceedings.

Becerik-Gerber, B., Jazizadeh, F., Li, N., and Calis, G. (2012). Application areas and data requirements for BIM-enabled facilities management. *Journal of Construction Engineering and Management, 138(3)*, 431-442.

Belsky, M., Sacks, R., and Brilakis, I. (2016). Semantic Enrichment of Building Information Modeling. *ComputerAided Civil and Infrastructure Engineering 31*, 261–274

Cheng, M.-Y., Chiu, K.-C., Hsieh, Y.-M., Yang, I. T., Chou, J.-S., and Wu, Y.-W. (2017). BIM integrated smart monitoring technique for building fire prevention and disaster relief. *Automation in Construction, 84(Supplement C)*, 14-30.

Codinhoto R., and Kiviniemi A. (2014) BIM for FM: A Case Support for Business Life Cycle. *11th IFIP International Conference on Product Lifecycle Management (PLM)*, Yokohama, Japan. pp.63-74.

Collinge, W.H.; OsorioSandoval, C. Deploying a Building Information Modelling (BIM)-Based Construction Safety Risk Library for Industry: Lessons Learned and Future Directions. Buildings 2024, 14, 500. https://doi.org/10.3390/buildings14020500

Department of Population Statistics. On work-related injuries and occupational diseases in the Republic of Kazakhstan. (2023). *Astana, Kazakhstan: Department of Population Statistics*.

Fargnoli, M., and Lombardi, M. (2020). Building information modelling (BIM) to enhance occupational safety in construction activities: Research trends emerging from one decade of studies. *Buildings, 10*(6). DOI: 10.3390/BUILDINGS10060098

Gambatese, J. A., Behm, M., and Hinze, J. W. (2005). Viability of designing for construction worker safety. *Journal of Construction Engineering and Management, 131(9)*, 1029-1036. DOI: https://doi.org/10.1061/(ASCE)0733-9364(2005)131:9(1029)

Gambatese, J. A., Behm, M., and Rajendran, S. (2008). Design's role in construction accident causality and prevention: Perspectives from an expert panel. *Safety Science, 46(4)*, 675-691.

Ganah, A., and John, G. A. (2015). Integrating Building Information Modeling and Health and Safety for Onsite Construction. *Safety and Health at Work, 6(1)*, 39-45.

Ganisen, S., Mohammad, I. S., Nesan, L. J., Mohammed, A. H. & Kanniyapan, G. (2015). The identificationof design for maintainability imperatives to achieve cost effective building maintenance: A delphi study. *Jurnal Teknologi, 77(30)*, 75–88. DOI: https://doi.org/10.11113/jt.v77.6871

Giel, B., and Issa, R. R. A. (2016). Framework for Evaluating the BIM Competencies of Facility Owners. *Journal of Management in Engineering, 32(1)*, 04015024. doi: 10.1061/(ASCE) ME.1943-5479.0000378

Goh, Y. M., and Chua, D. K. H. (2009). Case-Based Reasoning for Construction Hazard Identification: Case Representation and Retrieval. *Journal of Construction Engineering & Management, 135(11)*, 1181-1189.

Goh, Y. M., and Chua, D. K. H. (2010). Case-Based Reasoning Approach to Construction Safety Hazard Identification: Adaptation and Utilization. *Journal of Construction Engineering & Management, 136(2)*, 170-178. DOI: https://doi.org/10.1061/(ASCE)CO.1943-7862.0000116

Gondia, A., Moussa, A., Ezzeldin, M., & El-Dakhakhni, W. (2023). Machine learning-based construction site dynamic risk models. *Technological Forecasting & Social Change, 189*, 122347.

Hong-lin, G. (2014). Integrated Application of BIM and RFID in Construction Safety Management. Journal of Engineering Management. DOI: 10.13991/j.cnki.jem.2014.04.018

Hongling G., Yantao Y., Weisheng Z. and Yan L. (2016). "BIM and safety rules based automated identification of unsafe design factors in construction"

Hossain, M. A., Abbott, E. L. S., Chua, D. K. H., Nguyen, T. Q., and Goh, Y. M. (2018). Design-for-Safety knowledge library for BIM-integrated safety risk reviews. *Automation in Construction, 94*, 290-302. DOI: https://doi.org/10.1016/j.autcon.2018.07.010

Ku, K., & Mills, T.H. (2010). Research needs for Building Information Modeling for Construction Safety.

Kulinan, A. S., Park, M., Aung, P. P. W., Cha, G., & Park, S. (2024). *Advancing construction site workforce safety monitoring through BIM and computer vision integration*. Automation in Construction, 158, 105227. https://doi.org/10.1016/j.autcon.2023.105227

Kivits, R.A. and Furneaux, C. (2013) BIM: Enabling Sustainability and Asset Management through Knowledge Management. *The Scientific World Journal, 2013*, Article ID: 983721. DOI:
http://dx.doi.org/10.1155/2013/983721

Lam, K. C. (2001). Quality Assurance System for Quality Building Services Management. *Asia Pacific Building and Construction Management Journal*.

Leveson, N. (2004). A new accident model for engineering safer systems. *Safety Science, 42(4)*, 237-270. DOI: https://doi.org/10.1016/S0925-7535(03)00047-X

Liu, H., & Tian, G. (2019). Building engineering safety risk assessment and early warning mechanism construction based on distributed machine learning algorithm. Safety Science, 120, 764–771. https://doi.org/10.1016/j.ssci.2019.08.022

Malekitabar, H., Ardeshir, A.,Hassan, M.S. and Stouffs, R. (2015). Construction safety risk drivers: A BIM approach. *Safety Science. 2016*; 82:445–55. DOI: https://doi.org/10.1016/j.ssci.2015.11.002

Moatari-Kazerouni, A., Chinniah, Y., and Agard, B. (2015). Integrating occupational health and safety in facility layout planning, part I: methodology. *International Journal of Production Research, 53(11)*, 3243-3259. DOI: https://doi.org/10.1080/00207543.2hong014.970712

OSHA. (2022). Census of fatal occupational injuries summary, 2021 - 2021 A01 results. U.S. Bureau of Labor Statistics. https://www.bls.gov/news.release/cfoi.nr0.htm

Pishdad-Bozorgi, P., Gao, X. and Eastman, C., (2018). Planning and developing facility management- enable building information model (FM-enabled BIM). *Automation in Construction, 87*(Mar.), 22-38. DOI: https://doi.org/10.1016/j.autcon.2017.12.004

Rajaprasad, S. V. S., & Mukkamala, R. (2023). Prediction of Safety Performance by Using Machine Learning Algorithms: Evidence from Indian Construction Project Sites. *International Journal of Sustainable Construction Engineering and Technology, 14*(4), 40-48.

Sacks, R., Ling, M., Raz, Y., Borrmann, A., Daum, S. and Kattel, U. (2017). Semantic Enrichment for Building Information Modeling: Procedure for Compiling Inference Rules and Operators for Complex Geometry. *Journal of Computing in Civil Engineering, 31*: 04017062. DOI: https://doi.org/10.1061/(ASCE)CP.1943-5487.0000705

Salzano, A.; Cascone, S.; Zitiello, E.P.; Nicolella, M. Construction Safety and Efficiency: Integrating Building Information Modeling into Risk Management and Project Execution. Sustainability 2024, 16, 4094. https://doi.org/ 10.3390/su16104094

Sharar, M., Agyekum, K., Manu, P., Che Ibrahim, C. K. I., Mahamadu, A. M., Antwi-Afari, M. F., & Danso, F. O. (2022). Design for Safety in Construction: A Study of Design Professionals in Kuwait. *International Journal of Building Pathology and Adaptation.* https://doi.org/10.1108/IJBPA-01-2022-0015

Simeone, D., Cursi, S. and Acierno, M. (2019). BIM semantic-enrichment for built heritage representation. *Automation in Construction, 97*: 122-37. DOI: https://doi.org/10.1016/j.autcon.2018.11.004

Teicholz, E. (2004). Bridging the AEC technology gap. *IFMA Facility Management Journal*, March-April.

Tixier, A. J.-P., Hallowell, M. R., Rajagopalan, B., & Bowman, D. (2016). Application of machine learning to construction injury prediction. *Automation in Construction, 69*, 102-114.

U.S. Department of Labor, Bureau of Labor Statistics. (2021-2022). Employer-Reported Workplace Injuries and Illnesses. Retrieved from https://www.bls.gov/iif

Wetzel, E. M., and Thabet, W. Y. (2015). The use of a BIM-based framework to support safe facility management processes. *Automation in Construction, 60,* 12-24. DOI: https://doi.org/10.1016/j.autcon.2015.09.004

Xiaer, X., Dib, H., Yuan, J., Tang, Y., and Li, Q. (2016). Design for Safety (DFS) and Building Information Modeling (BIM): A Review. *In Proceedings of the International Conference on Construction and Real Estate Management 2016, Guangzhou, China, 10–12 November 2017*; *pp. 69–80.*

Zhang, S. and Teizer., J. (2013). Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules. *Automation in Construction, 29*, 183–195. DOI: https://doi.org/10.1016/j.autcon.2012.05.006

Zhong, B., Chen G., Luo, H. and Xing, X. (2018). Ontology-based framework for building environmental monitoring and compliance checking under BIM environment. *Building and Environment, 141*: 127-42. DOI: https://doi.org/10.1016/j.buildenv.2018.05.046

Zhou Y., She J., Li L., Zhang L. and Zhang J. (2022) A Design for Safety (DFS) Semantic Framework Development Based on Natural Language Processing (NLP) for Automated Compliance Checking Using BIM: The Case of China. *Buildings 2022, 12*(6), 780. DOI: https://doi.org/10.3390/buildings12060780