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Safety Risk Management in LEED Building Construction: A BIM Based Approach

By

Pranita Pandurang Shinde

A Thesis

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2021

Safety Risk Management in LEED Building Construction: A BIM-Based Approach

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DECLARATION OF PREVIOUS PUBLICATION

I. Co-Authorship

I hereby declare that this thesis incorporates material that is the result of joint research, as follows:

This thesis was completed under the supervision of my advisor, Dr. Rajeev Ruparathna. In all cases, the key ideas, primary contributions, data analysis, and writing were carried out by the author. The contribution of the co-authors (advisor) was primarily through the provision of the broad research idea, review of results, participation in scientific discussion, literature review, and subsequently, in editing the presentation material.

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This thesis includes two original papers that have been previously published/ submitted for publication in peer-reviewed journal/ Conference, as follows:

Thesis Chapter	Title	Publication Status
1 and 2	Shinde, P., and Ruparathna R., (2020). “A BIM-Based Approach for Life-Cycle Health and Safety Management in LEED Certified Buildings”.	Accepted/ Published

3	Shinde, P., and Ruparathna R., (2020). “Safety Risk Analysis of LEED Credits, International Journal of Construction Management”.	Completed
4	Shinde, P., Ruparathna, R. (2021) “Impact of Project Parameters on the Safety Risk of Green Construction Projects”, Journal of Management in Engineering.	Completed

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ABSTRACT

Green buildings have been gaining popularity in the construction industry due to their low impact on the environment. Green buildings are aimed at creating energy-efficient, healthy, and environment-friendly buildings. However, OSHA records show that about 48% more accidents occur in green building construction as compared to traditional construction methods. Compromising the workers' health and safety questions the "true sustainability" of the building. Green buildings have been a popular strategy in institutional sustainability agendas. Globally, LEED is the most popular green buildings rating system. Statistics show that an increasing number of construction projects intend to obtain the LEED certification in the next decade. However, elevated worker health and safety risks have been gradually becoming a concern while pursuing LEED credits. However, there exists a limited study comparing the safety hazards occurring in conventional construction practices and green construction practices.

This research explores the major safety risks associated with LEED-certified building construction. Failure Mode Effect, Analysis (FMEA) is used to determine the safety risk associated with each LEED credit. LEED credits were ranked based on safety performance. Safety score and incremental cost of LEED credits were used to identify the optimal credit combination for LEED gold certification that reduces the safety risk and minimizes the cost. Bayesian Belief Networks (BBN) was used to analyze the impact of project factors on safety risk. This analysis identified how the risk level of LEED credits changes based on project parameters. Safety risks identified from FMEA and BBN were used to develop Building Information Modelling (BIM)-based solutions to improve worker safety. The outcomes of this research will address the challenges of LEED construction and inform the construction industry in enhancing the health and safety of construction workers with state-of-the-art technology.

DEDICATION

This thesis is dedicated to my parents, uncle, and sister for their unconditional love and encouragement throughout all my endeavors. Without them, none of this would be possible and I thank them for all that they do for me.

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LIST OF ABBREVIATIONS/SYMBOLS

LEED : Leadership in Energy and Environmental Design
BREEAM : Building Research Establishment Environmental Assessment Method
BIM : Building Information Modelling
FMEA : Failure Mode Effect Analysis
BBN : Bayesian Belief Network
OSHA : Occupational Safety and Health Administration
RIR : Recordable Injury Rate
WGBC : World Green Building Council
RFID : Radio Frequency Identification
GIS : Geographic Information System
PtD : Prevention through Design
DfS : Design for Safety
VOC : Volatile Organic Compounds
RPN : Risk Priority Number
CEI : Centre for Engineering Innovation
DAG : Directed Acyclic Graph
IAQ : Indoor Air Quality
GHG : Green House Gases
AEC : Architecture, Engineer and Construction
CPT : Conditional Probability Table
USGBC : United States Green Building Council
SIM : System Information Modelling
MOO : Multi-Objective Optimization
USEPA : United States Environmental Protection Agency
CBR : Case-Based Reasoning
API : Application Programming Interface
IELD : Information conversion and Process Integration
ICPI : Information Conversion and Process Integration
ASPG : Auto Modelling and Safety Plan Generation

COBIE	: Construction Operation and Building Information Exchange
RTRL	: Real Time Resource Location
VP	: Virtual Prototype
BLE	: Bluetooth Low Energy
CNC	: Critical Number Calculation
PSO	: Particle Swarm Optimization
GA	: Genetic Algorithm

CHAPTER 1

INTRODUCTION

1.1 Background Information

The construction industry has a major impact on the triple bottom line of sustainability. Statistics show that the construction sector produces 30% of Greenhouse Gases (GHGs), generates 45 - 65% of waste deposited in landfills, produces 35% global CO_2 emmisions, consumes 20% of potable water (Lima et al., 2021)**.** Consequently, the construction industry has been striving to become a greener industry. Green buildings have received global attention in the recent past. The U.S. Green Building Council (USGBC) defines green building as a practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life cycle, from siting to design, construction, operation, maintenance, renovation, and deconstruction. This practice expands and complements the classical building design concerns of economy, utility, durability, and comfort. Medineckiene et al. (2010) defined sustainable buildings as encompassing five features: energy efficiency, water management, protection of the environment, indoor air quality, and sustainable practices. Green buildings have been the most popular sustainability strategy in organizational sustainability agendas. The true essence of sustainability lies in maintaining conditions under which humans and nature can exist in a productive way (USEPA 2006). Workers are an integral part of the construction, and their safety is as important as the occupants'.

As per the definition, green building is a vague concept. Green building rating systems such as Leadership in Energy and Environmental Design (LEED) and Building Research Establishment Environmental Assessment Method (BREEAM) have been developed to address this challenge (Zuo & Zhao, 2014). Currently, LEED is the most popular green building certification system, globally. LEED certification entails eight categories, namely, design processes of building and site, energy consumption, indoor atmosphere, material selection, water management, commissioning, upkeeping, and operation (Kubba et al., 2019). Scofield (2009) stated that LEED-certified buildings consume 18-39% less energy compared to traditional buildings. LEED certification has four levels (i.e., certified, silver, gold, and platinum) (Kim et al., 2018). LEED certification is used in more than 155 nations (Wu et al. 2017). More than 8,000 LEED-certified buildings are registered and certified in Canada. More than 2.65 billion m^2 floor space has been certified around the world (WGBC 2017/18). Many public and private sustainability agendas require obtaining LEED certification for future building construction.

However, recent research has identified an elevated safety risk level in green building construction when compared to conventional building construction (Fortunato et al., 2012). According to Walter et al. (2011), workers in green building construction have 39% more strains and lacerations. Strains and lacerations are caused due to the activities involved in construction waste management. 24% more falls from activities such as installing PV panels and vegetating roofs, 19% more conflict incidents, and 13% more exposure to hazardous substances occuring from wastewater treatment or cleaning up contaminated sites. Karakhan and Gambatese (2017) identified a similar trend in LEED projects where specific green construction methods used in LEED impose a high safety hazard to construction workers. As an example, the use of recycled material gains LEED credits based on applied strategies. However, considerable injuries can be caused during recycling due to handling, sorting, and transporting (Rajendran et al, 2009). The above statistics on worker safety challenge the "true sustainability" of a green building (Boulder, 2016). Being a labour-intensive industry, the success of a construction project depends heavily on the labour force (Hinze et al., 2013). Therefore, construction managers should seek strategies to enhance worker safety in LEED building construction. Detailed case studies have been carried out to indicate how workers are exposed to high-risk tasks on LEED projects. These case studies reveal workers' exposure to hazardous materials, unstable earth, and soil conditions, causing slips, trips, and collapse. Several LEED credits require that workers work on heights and roof slopes (Fortunato et al., 2012). Evidence found by Rajendra

(2009) states a 48% rise in Recordable Injury Rate (RIR) during the construction of green buildings compared to non-green buildings. BIM has the ability to address site safety aspects effectively using coherent tools, ease of communication, and dynamic procedures (Enshassi et al., 2016). In the construction industry, hazard identification is an essential application of the most promising feature of BIM, which is visualization (Akram et al., 2019).

Over the years, Building Information Modelling (BIM) has become an essential technology in the construction industry. BIM can be used for construction safety management by integrating with other technologies such as sensors, augmented reality, virtual tracking, and gaming applications to identify and mitigate worker safety risks (Martínez-Aires et al., 2018; Cheng & Deng, 2015). Previous researchers have used BIM to simulate evacuation during emergencies (Zhang & Issa 2015), provide hazard visualization and safety training (Jalaei & Jrade, 2014), model temporary structures to ensure their safety (Cheng & Deng, 2015), and evaluate and predict safety hazards, such as falls (Zhang et al., 2015). BIM tools can be used with green buildings for energy performance analysis, lighting analysis, and construction and demolition waste management (Lu et al., 2017). BIM delivers precise calculations of data and information required for green buildings. The study by Huang et al. (2021) revealed 87% of the respondents claim BIM can be used reasonably in green building construction for simulating construction processes; however, a direct approach to green building safety culture using BIM remains uncertain and perplexing.

1.2 Knowledge Gap

The premise for this research was defined based on the following knowledge gaps identified in the literature:

1.2.1 Lack of research on safety hazards associated with individual LEED credits

Previous researchers have not analyzed and compared the safety impact of individual LEED credits (Karakhan, 2016; Gambatese et al, 2017). Hinze et al. (2013) raised the question of whether a building that meets all the prerequisites prescribed by an organization should be called a green building, irrespective of the number of injuries and fatalities caused during the construction. Although Rajendran et al. (2009) provided some evidence of safety hazards associated with green buildings, the study did not provide a critical examination of individual credit. While the current literature focuses on distinguishing between traditional construction methods and green construction methods of building execution, it lacks comprehensive analysis of the risk level, causes, impacts, and mitigation methods.

1.2.2 The causality of project parameters on the safety impacts related to LEED credits has not been researched

Current literature has overlooked the causes and effects of the safety hazards and their inadequate assessment associated with LEED credits (Fortunato et al., 2012). An assessment conducted by Karakhan (2016) analyzed LEED-certified projects to investigate which construction method poses the highest RIR. Even though this study investigated hazardous LEED credits based on impact levels, activities causing the hazards were overlooked. Fortunato et al. (2012) reviewed safety issues associated with LEED credits. However, this study did not perform a quantitative and qualitative analysis of causes and sub-causes related to safety hazards. Construction project parameters (e.g., worker skill level) impacts the probability of occurrence of the safety hazards associated with them. Critical risks corresponding to different project settings can be identified by detailed investigation of project parameters.

1.2.3 The use of BIM-based safety management in LEED-certified buildings has been overlooked by academia

BIM can assist in planning for LEED points and support in project-related decision making (Jalaei & Jrade, 2015). Even though

BIM-based safety management has been popular for general construction, specific applications for LEED construction have been overlooked (Zhang et al., 2015).

1.3 Motivation

The demand for green buildings has influenced the growth in applications for LEED certification. However, the current literature indicates a higher injury rate in LEED buildings compared to non-green buildings (Hwang et al, 2018; Benjaoran & Bhokha, 2010). This study is motivated by the growth in the demand for LEED certification over recent years. Rajendran and Gambatase (2009) emphasized that a building can be considered truly sustainable if worker health and safety are considered as an integral part. Worker safety ensures the smooth progression of a construction project (Benjaoran & Bhokha, 2010). On the other hand, poor safety management results in insecurity of workers and their families and affects the efficiency of workers and thus the overall success of a project (Awolusi & Marks, 2017).

1.4 Objective

The vision of this research is to safeguard the construction workers who work on LEED building projects. This research has investigated the causality of safety hazards in LEED construction and proposed preventive measures to increase safety. The following sub-objectives are achieved in each phase of the thesis.

i. Identify construction hazards and impacts associated with obtaining LEED credits
ii. Perform Failure Mode Effect Analysis (FMEA) to compare the safety risk of LEED credits
iii. Identify optimal LEED credit combination that reduces safety risk and implementation cost
iv. Analyze the impact of project parameters on the safety risk of LEED credits
v. Propose BIM-based solutions to improve the safety performance of

LEED-certified building projects

1.5 Research Methodology

This research study was designed with the intent to analyze the safety hazards related to green buildings broadly. The knowledge of current literature was used to identify data that will be used to analyze and generate conclusions. Figure 1-1 illustrates the methodology adopted in this research. Four interrelated phases will be used to achieve the objectives of this research.

Phase 1 included the literature review and data collection. This phase comprised of actual data collection and data exploration. Published literature was used to identify the causality of safety hazards. The Occupational Safety and Health Administration (OSHA) and the Canadian Centre for Occupational Health and Safety (CCOHS) were reviewed. Moreover, the selected data were then sorted and categorized according to the research requirements.

Phase 2 comprised Failure Mode Effect Analysis (FMEA). FMEA provided risk scores for selected LEED credits. These LEED credits were ranked based on risk scores.

Phase 3 was aimed at identifying the LEED credit combination for LEED gold certification that minimizes the cost and safety hazard. This phase of the thesis identified the most efficient LEED credit combination based on the above objective.

Phase 4 assessed the impact of project parameters on LEED credits. Bayesian Belief Networks (BBN) were used to determine how the highest risk LEED credit changes with project parameters.

In Phase 5, BIM-based solutions were proposed for the main safety risks identified in Phase 2. These solutions were customized to LEED building construction.

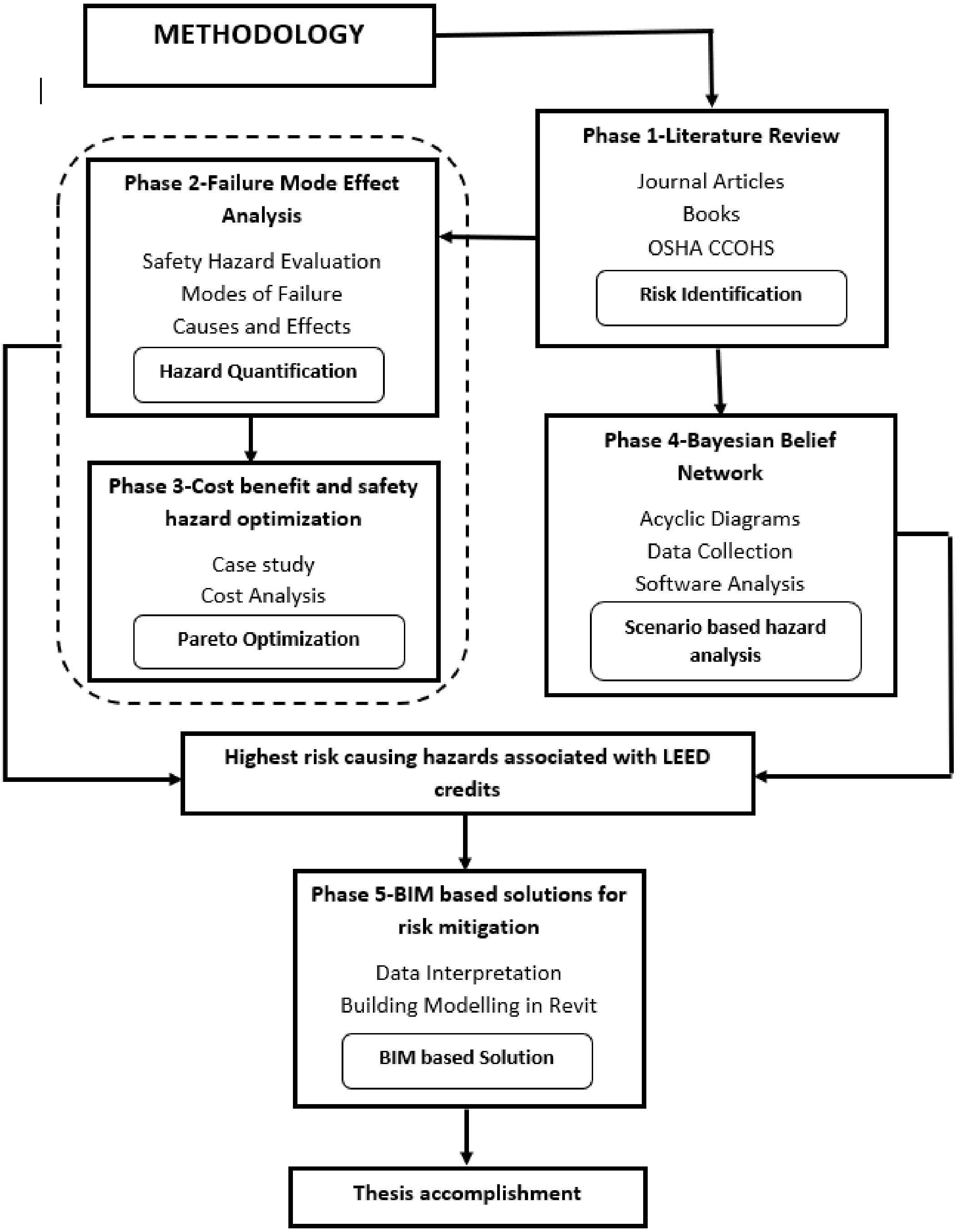

Figure 1-1 Research Methodology

1.6 Thesis Organization

This thesis is structured into seven chapters.

i. Chapter 1 presents the background information of this research. This chapter explains the knowledge gap, motivation, objectives, and overall methodology.

ii. Chapter 2 provides background literature on BIM-based safety management in green building construction. The shortcomings and the outcomes of the present literature are discussed.

iii. Chapter 3 presents the Failure Mode Effect Analysis (FMEA) of individual LEED credits. This assessment considers the causes, sub-causes, effects, and modes of failure, and ranks LEED credits based on the safety score.

iv. Chapter 4 presents a method to determine the optimal LEED credit combination based on incremental costs and safety hazards.

v. Chapter 5 presents BBN to investigate the impact of project parameters on worker safety. The risk variability, according to project parameters, is subsequently presented.

vi. Chapter 6 provides a BIM-based solution to mitigate the safety risks in LEED-certified projects. Best management practices and implementation guidelines for identified safety solutions are proposed.

vii. Chapter 7 presents the conclusions of this research. Moreover, limitations and future research areas are discussed.

Chapter 3 evaluates the risk level for each hazard causing LEED credit using FMEA. The results of Chapter 3 are used in Chapter 4 for performing optimization of workers health and safety and LEED implementation costs. Chapter 5 uses data from FMEA to investigate the impact of project parameters on the probability of occurance of safety hazards. Chapter 6 proposes BIM based risk mitigation methods for critical risks identified in Chapter 3 and Chapter 4.

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Green Building Safety

The sustainability of a building project is now a measure of green rating systems. The level of rating obtained by a building decides the certification level of that building. This measure of sustainability is often argued by a few research articles (Karakhan & Gambatese, 2017a). The LEED certification being part of it was designed by the principles of resource efficiency, environmental conservation, and occupants' health (Rajendran et al., 2009). However, the morality of the term 'sustainability' is endangered due to the hazardous activities involved in the process of attaining the standards of green building (Hinze et al., 2013). The LEED certification system involves certain credentials that require workers to work at greater heights to reduce the heat island effect. Heat island effect is a credit which requires to reduce the area exposed to sunlight to minimize the heat absorption and heat transfer. This can be accomplished by vegetating roofs. Similarly, extra points are allotted by the certification system for managing construction waste. These types of activities involved in the LEED rating system pose dangers to workers' health and safety (Karakhan & Gambatese, 2017b). Working near unstable soils, heavy equipment, and rooftops for a long period were certainly the major causes of safety hazards (Fortunato et al., 2012). Although facilities such as permeable parking and paving were intended to enhance stormwater control, such working conditions may cause over-exertion and accidents to the workers (Karakhan & Gambatese, 2017a). Installing large windows and doors for efficient air delivery and installing glass roof atria for daylight improvements are examples of tasks that challenge the safety environment for workers (Karakhan & Gambatese, 2017a).

Workers' health and safety were categorized as a social parameter that has been overlooked by the rating systems and safety organizations. Although sustainability contributes to the health, environment, and economy of a construction project, the health and safety of workers were often overlooked by this term. Social dimensions should be considered during the assessment of the building for accreditation (Zuo & Zhao, 2014). Rajendran et al. (2009) performed a case study to compare non-green and green projects to determine the safety hazards caused by green and non-green building projects. He discovered a considerable increment in the injury and fatality rate of green buildings up to 48%. According to a survey conducted in Singapore by Hwang et al., (2018) among various known construction companies, safety issues such as 'being struck by falling object', 'respiratory failure', and 'exposure to hazardous substances' were severe in green building projects as compared to conventional construction. This study concluded there is a higher risk involved in green building construction methods (Hwang et al., 2018).

2.2 Occupational Health and Safety in the Construction Industry

The occupational health and safety act of 1970 states that "Recommending and encouraging states to ensure a healthy and safe working environment for all irrespective of the gender by adopting rules and regulations developed under the act. The act was amended with a provision to deliver education and training in the field of occupational health and safety and encourage research and information in the same." However, the European Union first implemented safety management systems in the construction industry by 1980. It started by establishing safety committees to identify and analyze the risks and encouraging health and safety programs (Yiu et al., 2019). To diminish the fatality and injury rate, engineering controls as well as behavioral practices were executed (Nnaji & Karakhan, 2020). Safety performance indicators were used to improve safety performance. Accident reporting, near-miss investigation, and assessing site safety during the planning and designing phase to avoid possible hazards were some other frameworks developed by the construction industry (Choe et al., 2020). According to Choudhry et al. (2008), managing the site using a defined safety organization structure can be the best practice to avoid accidents and injuries. Considering the magnified benefits of technology and its multiple abilities, technology-based approaches were gaining popularity in the early 2010s (Nnaji &

Karakhan, 2020). The construction industry was now approaching safety management using digital and technology-based systems. Recently, a method of synchronizing the data between the onsite construction practices and virtual construction was accomplished to manage safety in a smart and less time-consuming way (Jiang et al., 2020).

Improving the health and safety of workers was one of the crucial objectives of the construction industry. Insufficient safety management often created adverse effects on the cost, directly or indirectly. It was proportional to the productivity of the work completed (Alkaissy et al., 2020).

2.3 Role of BIM in Safety Management

Building Information Modelling (BIM) is the most popular emergent technology that leads the construction industry to efficiently manage the life cycle of a constructed asset (Franco-Duran & Mejia, 2016). Recently, BIM have also been suggested as applying to construction safety management. A multitude of BIM-based safety management approaches has been proposed in the literature. Initially, BIM-based construction safety management was approached using simulation and virtualization methods. However, later BIM-based safety management has extended to 4D CAD, virtual reality, augmented reality, virtual tracking, gaming applications, radio frequency identification, cloud-based risk database, animation based modeling, DFS library rule base, and real-time resource location (Martínez-Aires et al., 2018). BIM dealt with many challenges in construction management approaches. However, there is limited research in the field of safety and BIM (Akram et al., 2019). Table 2-1 illustrates the most common types of incidents and related attempts made to minimize them using BIM.

Table 2-1 BIM-based Mitigation Attempts for On-site Incidents

Sr.No.	**Type of Incidents**	**Reference**	**BIM-based mitigation attempts**
1	Visualization of crane reach areas	(Khoshnava et al., 2012)	Models on BIM platform identifying crane collapse
2	Fall from height	(Fang et al., 2018)	3D visualization was used to detect harness automatically
3	Wall collapse or destruction	(Khoshnava et al., 2012)	BIM-based wall prototype visualizing the demolition process
4	Collision detection	(Franco-Duran & Mejia, 2016)	Spatial-temporal conflicts were automatically detected using 3D visuals and workspace geometry data input.
5	Safety railings	(Khoshnava et al., 2012)	BIM-based modeling including other components like a guardrail
6	Fire emergency evacuation	(B. Wang et al., 2014)	Evacuation time and fire intensities were measured on the BIM platform
7	Formwork related safety	(Khoshnava et al., 2012)	BIM-based model showing formwork process and related safety concerns
8	Fall detection	(Zhang, Sulankivi, et al., 2015)	Automatically identified dynamic conditions and locations using BIM
9	Noise hazard mapping	(Cheng & Deng, 2015)	Noise data was processed to visualize the noise predictions using BIM
10	Automatic slab edge and hole detection	(Zhang, Sulankivi, et al., 2015)	Rule checking algorithm using automated modeling
11	Hazardous exposure mapping	(Altaf et al 2014)	BIM was used to assess air pollutants to limit exposure

BIM enables effective safety management throughout the life cycle of a construction project. The following sections explain how BIM-based approaches have been used for safety management.

2.3.1 BIM in the pre-construction phase

Considering safety issues during the planning and designing phase reduced 71% of safety hazards. BIM was an effective way to enhance designing and planning strategies to safeguard workers from known and unknown hazards (Azhar et al., 2012). Safety Information Modelling (SIM) was developed for various hazard scenarios to guide safety management. SIM was a comprehensive attribute in BIM that classified safety rules, geographic information, schedules, and detailed categories related to safety (Leung et al., 2016). Many construction sites were not planned to prevent accidents. BIM was used to plan for a safer workplace that can be achieved using a BIM-based framework (Choi et al., 2014). Prevention through Design (PtD) was a method to determine safety and health hazards presumed to occur during the construction work. This approach was adopted in the design phase of construction using the 4D BIM assessment tool, which is a knowledge-based method (Jin et al., 2019).

The planning stage played a vital role in mitigating safety hazards occurring throughout the building life cycle. The risk database and the safety risks stored in the BIM cloud were compiled together to provide automatic risk identification in the pre-construction stages of a building (Li et al., 2018). In the predesign phase, planning to assign duties systematically to the admissible workforce, appropriate location, and equipment decided the direction of the whole project. BIM-based simulations enhanced the efficiency of planning, which has an indirect relationship to safety (Ham et al., 2008). Project sites in densely populated areas were often challenging for material handling, transportation, and worker conflicts. To prevent probable hazards due to space constraints, BIM-based site layout planning was adopted. BIM could visualize site layout and provide workflow ideas for material handling and transportation. It visualized confined and dangerous spaces to limit the safety risks for workers (Lota & Trivedi, 2019). Predictable safety risks were dealt with by site engineers using site layouts in the planning and designing phase. Onsite transportation was managed using site layouts in BIM to avoid accidents (Azhar et al., 2012).

2.3.2 BIM in the construction phase

The following 4D BIM was applicable to detect on-site collisions between workers and equipment using the method of spatial-temporal collision detection during the construction work (Zhexiong Shang et al., 2016). Temporary structures such as scaffolding were widely used in construction. As per OSHA records, 65% of workers were randomly working on scaffolding systems. Automatic design of scaffolding solutions minimized the risks of fall hazards, using BIM-based data integration (Kim & Teizer, 2014). Rule-based algorithm using BIM was a technique used for the prevention of falls from height. Manual BIM-based modeling was the key feature of this research (Zhang, Sulankivi et al., 2015). Fire breakouts were another risk posed during the construction phase and evacuation of workers was necessarily addressed using BIM. A serious gaming application supported by BIM provided guidelines for computing real-time fire evacuation (Zhang et al., 2015). Noise hazard, being a long-term health hazard for workers leading to temporary or permanent hearing loss, is not an exception for BIM. Noise hazard is left behind and insufficiently tracked in construction safety management. BIM was capable of mapping noise and producing visuals based on noise data (Cheng & Deng, 2015).

2.3.3 BIM in the post-construction phase

The operation and maintenance phase were as important as the preconstruction and construction phases, from the perspective of worker and occupant health and safety. Facility Management repeatedly posed high risks of falls, electrical shocks, bruises, and fire breakouts (Sampaio & Simões, 2019). Therefore, safety protocol was equally important to be conveyed for activities related to the post-construction phase. A BIM-based framework by Wetzel and Thabet (2015) was developed to convey appropriate lifecycle information to provide safe Operation and Maintenance (O&M) practices. Developing a combination of safety-related native BIM models and an adjoined BIM model was initiated by the design team. The BIM model was further supported by rule-based data, which gave safety protocols for any input activity (Wetzel & Thabet, 2018). The maintenance stage was susceptible to fire constantly, so a BIM-based analysis via augmented reality helped provide precise and quick information to check equipment operability (Chen et al., 2020). In the case of maintenance and operation, BIM models used for planning, designing, and construction helped to carry out post-construction processes more efficiently.

2.4 Review of BIM-based Methods in Safety Management

2.4.1 Algorithm approach

A safety check for fall detection and preventive measures using the BIM approach was carried out for two case studies. With the help of an algorithm, probable fall orientation was visualized in BIM. Hazard identification and hazard elimination were the two important features of this approach. Data assesment is performed by linking an algorithm with BIMmodel (Zhang, et al., 2015). During the planning and designing stage, if risks are pre-determined, they can be efficiently tackled. The paper used manual modeling and automated modeling for risk mitigation and concluded the merits and demerits of both (Zhang, Sulankivi, et al., 2015). VC_COLLIDE algorithm was an approach used in BIM to deal with safety issues concerning collisions between stationary and mobile objects on-site, and it also had the ability to calculate the safe distance to prevent the risk. SIMCOM+ was a tool that created a context anatomizing temporary structures, workplace, and workers to ensure safety mitigation. This method used a database that included safety rules, algorithms, and object-specific regulations on the BIM platform, programmed with the help of a user interface to tackle safety issues in the construction industry (Ganah & John, 2017). Work breakdown structure was used to create work areas that should be assigned to specific activities using BIM. Activities were assigned to these workspaces individually, allotting the number of workers, equipment, material, etc. Based on this criterion, potential risks were determined by applying risk simulation processes to the workspaces. After evaluating the risks, safety measures in the form of dynamic virtual fences were applied (Melzner et al., 2013).

2.4.2 Radio frequency identification

The assimilation of BIM with another technology was an ultimate booming advantage. Such advancement was made possible using Radio Frequency Identification (RFID). RFID and BIM worked together to form a prototype showing possible risks and gathered data related to safety norms in a strenuous manner on real-time scale respectively (Binyong et al., 2018). If indoor positioning of workers and movables is achieved, conflicts among them can be avoided to a large extent. But the execution of positioning systems has always been a challenge for researchers. Various technologies have been working on this such as inertial navigation systems, ultra-wideband, RFID, etc. RFID and BIM supported each other to overcome the safety management crisis more practically. RFID sensors were tagged on workers and movables so that conflicts and collision were recognized (Fang et al., 2016).

2.4.3 Cloud-based risk database

BIM-cloud-based risk database was created to store heavy databases associated with safety hazards, from which engineering information was extracted to define related risks. The engineering information stored in the BIM cloud was linked with safety issues classified based on essential parameters. Finally, automatic safety risk detection operation was established on a pre-determined confidence level (Li et al., 2018). Apart from construction activities, maintenance activities were also taken seriously by few researchers. Data in the form of knowledge and BIM were integrated to provide information about after/before maintenance work. This technique helped to decide preventive measures and required repair works to be undertaken. It was a product of two parameters: BIM and Case-Based Reasoning (CBR) (Motawa & Almarshad, 2013).

2.4.4 Animation based modeling (Visualization)

The BIM approach was implemented in fire safety and evacuation circumstances. The BIM input module was prepared in accordance with a serious game application. Location and fire intensity were set for the player. Factors such as time taken by the player to escape, length of the evacuation path, and shortest distances were collected in the form of data. Based on this formula, trial designs were tested to achieve minimum evacuation time (for example, the width of a corridor can be increased, an exit door must be installed closer to the fire breakout) (Zhang & Issa, 2015). BIM-based 3D visualization was used to demonstrate safety training to the workers. It was especially useful in scaffolding tasks where major falls occur. Mid-rail height and minimum plank width for trainees were demonstrated using animation supporting BIM (Jalaei & Jrade, 2014). A recently published paper introduced BIM and Geographic Information System (GIS) technology used in the areas of sustainable construction. BIM-GIS was defined as, “BIM leads, and GIS supports,” “GIS leads and BIM supports,” and “BIM and GIS lead together.” By creating four arms, namely, data integration, energy management, urban governance, and lifecycle of a project to the BIM and GIS integration, a sustainable built environment was created. There can be prominent research in the BIM-GIS field due to its promising features and benefits (Wang et al., 2019).

Temporary structures such as stair towers utilized for roof construction were usually considered unsafe. To improve safety threats caused by temporary structures, BIM was integrated. Required geometric and non-geometric parameters of the temporary structures were visualized using a set of algorithms. Algorithms were lodged onto the BIM interface to analyze the safety hazards related to temporary structures (Cheng & Deng, 2015). The work was divided into four phases. The first phase involved ascertaining various acts involved in scaffolding. The second phase was to carry out an informative quiz from experts. In the third phase, risks associated with scaffolding were defined by collaborating BIM and a systematic algorithm. Finally, risks were integrated into the BIM safety visualizer plug-in, and mitigation measures were suggested (Rachel et al., 2014).

2.4.5 DFS Library

Deriving a rule-based DFS library in which safety rules were set based on geometric or physical constraints was an asset to BIM integration. Concepts like meta-rule and atomic rule have established a convenient systematic approach in the DFS library. Thus, safety rules from the library were amalgamated into BIM to analyze risks in the design phase itself (Hossain et al., 2018). This paper instigated a rule-based checking system, an interface that supports BIM to apply safety rules by evaluating the model. This was an automatic system that needs an algorithm to be developed along with an Open Application Programming Interface (API). Tecla structures were chosen for the implementation of safety checks (Zhang et al., 2013).

Excavation planning in the construction industry was still not taken seriously from a safety point of view, providing technological advancements that we use in other construction activities. BIM was efficiently applied for safety planning for excavation activity with help of algorithmic modeling tools. These papers essentially focused on falls, safety departures, safety details or prohibited zones, and cave-ins. A set of rules was instigated in software that can visualize potential imminence and safety installations. Information Extraction and Logic Design (IELD), Information Conversion and Process Integration (ICPI), and Auto Modeling and Safety Plan Generation (ASPG) were the three constituent perspectives in this research (Khan et al., 2019).

Literature for the application of BIM in the construction industry was popularly available but very less concern was observed in operation and maintenance work safety. BIM was used to visualize the selection of suitable equipment during operation and maintenance work to ensure safety. For example, after defining the height of an object to be installed or removed, the use of proper equipment such as a ladder, lifting crane, etc. was examined by visualizing the process in BIM (Lauria, 2018). The evolution of Safety Information Modelling (SIM) concerning BIM was an exclusive method to improve the effectiveness and proficiency of construction safety management. SIM was developed by virtue of BIM with help of a questionnaire, survey, case studies, etc. to allow automated safety management (Leung et al., 2016).

Configuration was developed on the BIM platform to identify violations of rules and regulations applied for safety, performed by workers, to minimize accidents on the construction site. A questionnaire survey, focus group study, and the implementation of the method for a case study was the methodology of this research paper (Petronas, 2018). Combining design information and planning information, a rule-based system was adopted that helped to detect hazards related to height risks. Models were created based on the safety rules, which were programmed into the construction schedules. 4D CAD models visualized risks associated with ‘fall from height’, the most known incident causing most of the accidents (Benjaoran & Bhokha, 2010).

Visualization of possible risks in BIM during the designing stage eliminated maximum possible fatalities. Possible dangerous locations or zones were effectively identified. Tower crane orientations were determined, and probable hazards were avoided using BIM visualization in the planning and designing phases. In the case of fire safety, BIM determined the minimum and maximum distance for evacuation exits (Cherkina et al., 2018). In 2014, Construction Operation Building Information Exchange (COBie) was introduced in the field of construction management to exchange information. It effectively dealt with safety management by exchanging data with BIM. COBie was only capable of providing information in the form of data and does not form a prototype (Park & Kim, 2015).

A safety management system was incorporated with BIM to reduce human penalties in high rise buildings. The system was developed in three main stages: 1. Data collection, which was presented as ‘data module’; 2. Organizing construction security, represented as ‘security management module’; and 3. BIM modeling, called ‘BIM virtual construction module’. Further, the potential risks were identified, and dangerous areas were determined. Based on the measurable data, the safety control system was executed (Wang et al., 2018). PtD encouraged the designers to design for safety, where designers play a promising role in the prevention of safety risks. PtD was a method that can be applied in integrating risk profiles to create an 8D model. This included three steps to initialize with: 1. Creating a profile of risks related to various construction elements, 2. Applying safety mitigations to them, and 3. Along with the previous two strategies, a risk profile for unstoppable hazards even after updated designs was to be prepared (Kamardeen, 2010). When BIM modeling was integrated with a set of rules, proper information about safety management is expected to get precise results. To meet this demand, an ontology was proposed to organize, re-store, and reuse safety information. The ontology application was proceeded with modeling to determine the effectiveness of the proposed ontology. Questionnaires and surveys were conducted to decide the framework and content of the ontology (Zhang, Boukamp, et al., 2015).

2.4.6 Real-time resource location (RTRL)

Construction equipment such as cranes, ladders, and other movables pose danger to the workers on the site. Determining blind spots and minimum visibility regions of an operator helped reduce this danger by visualizing hidden hindrances using BIM. In addition to visualizing construction activity, this research paper promotes the use of real-time virtual reality using sensors. This paper made use of real-time data collection followed by data processing. Modeling the live activities and then suggesting safety precautions for hazardous activities was the objective of the study (Cheng & Teizer, 2013). On-site safety was ensured by establishing dangerous locations and visualizing them in BIM. The same approach was used by Batson et al. (2017), who focused on three prime elements: 1. Near miss reporting, 2. Automatic hazardous proximity zone generation, and 3. Site location optimization.

2.4.7 Automation/ Simulated-based

Working on scaffolding was one of the most dangerous activities many research papers have tried to overcome with ultimate safety solutions. The paper established an automatic scaffolding model by identifying geometric requirements. Unlike other research ideas where provisions for the proper design of scaffolding were made, this research strived to increase the limits of atomization for scaffolding activities, which was a product of a pre-determined set of rules (Kim & Teizer, 2014). Virtual Prototype (VP) was a modeling and simulation-based method in which 2D models were converted into 3D models. From 3D models, unsafe spaces were identified using VP-based hazard identification, while unsafe operations were identified from the simulation process by creating a construction schedule (Guo et al., 2013).

2.4.8 Sensor Technique

During fabrication and construction processes, clashes between workers, equipment, or machinery were observed. To overcome this safety issue, BIM was used effectively to detect conflicts among cranes, vehicles, and workers. “Spatial-Temporal Conflict Detection” by Franco-Duran and Mejia (2016) introduced a BIM-based technique to design safe methods of execution. The workplace on the construction site was represented in the form of a 3D model, then collision data was generated for safety analysis. Manual supervision on construction sites was not always enough to limit accidents or even identify them before they occurred. Efforts are being made using BIM to detect possible hazards on construction sites. BIM technology was integrated with some upgraded methods for identifying risks. One of those was the use of BLE mobile tracking sensors. BLE stands for Bluetooth Low Energy, which was based on the position detection concept (Park et al., 2017). BIM was an effective tool to mitigate safety measures to deal with scaffolding and related activities.

Table 2-2 illustrates how BIM-based applications were incorporated by previous research to minimize safety hazards in the construction industry. Prominent BIM-based techniques were being studied by the authors listed in Table 2-3.

Table 2-2 Methods associated with BIM approach

Reference	**Methods**								**Remark**
	Algorithm	**Radio Frequency Identification**	**Cloud-based risk database**	**Animation based modeling. (Visualization)**	**DFS library Rule base**	**Real-time resource location**	**Automation/ Simulation based**	**Sensor technique.**	
(Zhang, et al., 2015)	✓								Set of problem-solving operations that are broken down into phases. Building Information Modelling and Algorithmic design influences the design procedure
(Batson et al., 2017)	✓								
(Ganah & John, 2017)	✓								
(Melzner et al., 2013)	✓								
(Binyong et al., 2018)		✓							This method allows us to use frequency matching competency
(Fang et al., 2016)		✓							
(Li et al., 2018)			✓						Consists of a database that uses a cloud computing platform
(Jalaei & Jrade, 2014)				✓					Animations are used to support BIM

(J. Zhang & Issa, 2015)	✓		Gaming in a serious way to show smoke evacuation strategies using BIM
(Cheng & Deng, 2015)	✓		Data integration and Visualization
(Wang et al., 2019)	✓		Data integration and Visualization
(Hossain et al., 2018)		✓	Design for safety is a library consisting of rules to prohibit hazards and integrated with BIM for visualization
(Khan et al., 2019)		✓	
(Kamardeen, 2010)		✓	
(Lauria, 2018)		✓	
(Leung et al., 2016)		✓	
(Petronas, 2018)		✓	
(Cherkina et al., 2018)		✓	
(Park & Kim, 2015)		✓	
(Benjaoran & Bhokha, 2010)		✓	
(Wang et al., 2018)		✓	

(Zhang, Boukamp, et al., 2015)	✓				
(Cheng & Teizer, 2013)		✓			Determination of blind spots and poor visual areas is possible using this method in collaboration with BIM
(Kim & Teizer, 2014)			✓		Automatically creating safe designs for scaffolding activity
(Franco-Duran & Mejia, 2016)				✓	
(Guo et al., 2013)			✓		Automatic Virtual Simulation
(Park et al., 2017)				✓	Sensing locations or positions and visualizing probable conflicts, collisions amongst workers and equipment is achieved by this method

2.5 Summary

Digital technologies in design, planning, and execution have been getting popular in the construction industry. BIM can play a vital role in ensuring the health and safety of workers. This chapter explores an overlooked area in green buildings construction and discusses the necessity of safety management in green buildings. This chapter also highlights how the implementation of BIM can raise construction safety to new heights.

Techniques such as algorithms, DFS library, cloud-based risk database, and sensor techniques were extensive in the current literature. The use of BIM in the early planning and designing stage was considered to be highly influential in managing workplace safety. This chapter accentuates onsite incidents and BIM-based executed trials to tackle onsite accidents.

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CHAPTER 3

SAFETY RISK RANKING OF LEED CREDITS

3.1 Introduction

Occupational health and safety are major concerns in the construction industry. Hence, worker safety is an important social aspect to be considered in green building construction. Mapping the intensity and consequences of occupational hazards can help better safety management of the workplace (Alizadeh et al., 2015). LEED-certified buildings have improved occupants' health and reduced the environmental impact. Green buildings possess long-term value and reduced maintenance costs (Karakhan, 2016). Moreover, government mandates and incentives have driven the green building and LEED certification systems to another level, but this rapid growth has left the impact of LEED on workers' health and safety unseen (Fortunato et al., 2012).

Hazard identification methods can be categorized as qualitative analysis and quantitative analysis (e.g. preliminary hazard analysis and fault tree analysis) (Liu & Tsai, 2012). The Failure Mode Effect Analysis (FMEA) method falls under the semi-quantitative analysis category. Causes of safety incidents in the construction sector include qualitative and quantitative data. Hence, FMEA is a feasible method for assessing the safety risk of LEED credits. FMEA has been used in a wide variety of applications such as healthcare failure mode for diseases (Kahraman, 2013), cost risk analysis (Lee & Kim, 2017), occupational psychochemical exposure assessment (Jung et al., 2019), and risk-based maintenance planning using FMEA (Cicek et al., 2010).

Preliminary hazard analysis, matrix method, tie line method are some other qualitative and semi quantitative methods of risk analysis. (Liu & Tsai, 2012).FMEA is an evaluation method based on probabilistic identity to define risk values with the help of severity and discernible guidelines (Ilbahar et al., 2018). FMEA is a gradational and gradual process of analyzing the effects, causes, and circumstances of a failure. FMEA is an effective tool used in the construction industry for risk management (Kahraman, 2013). The adoption of FMEA can help identify probable modes of failure and eliminate them from a system. The evaluation proceeds by quantifying the severity and the probability of occurrence (Lee & Kim, 2017).

This chapter will focus on the evaluation of safety hazards associated with LEED credits. FMEA was used to determine the activities and safety risks related to LEED credits. It also provided an insight of causes and the impacts of the accidents. This research informs the construction industry on the level of safety risk associated with LEED points.

3.2 Methodology

FMEA delivered both knowledge and analysis of the risk level for each hazard. FMEA followed three important steps: analyze the system process, identify the potential failures, and examine the severity of the effects and causes (Cicek et al., 2010). Initially, events and activities were critically examined that were responsible for the modes of failure. Further analysis was performed with the help of the literature and published articles to assign the linguistic ranges in terms of occurrence and consequences. The step-by-step procedure of FMEA is illustrated in Figure 3-1. Each step is explained in detail below.

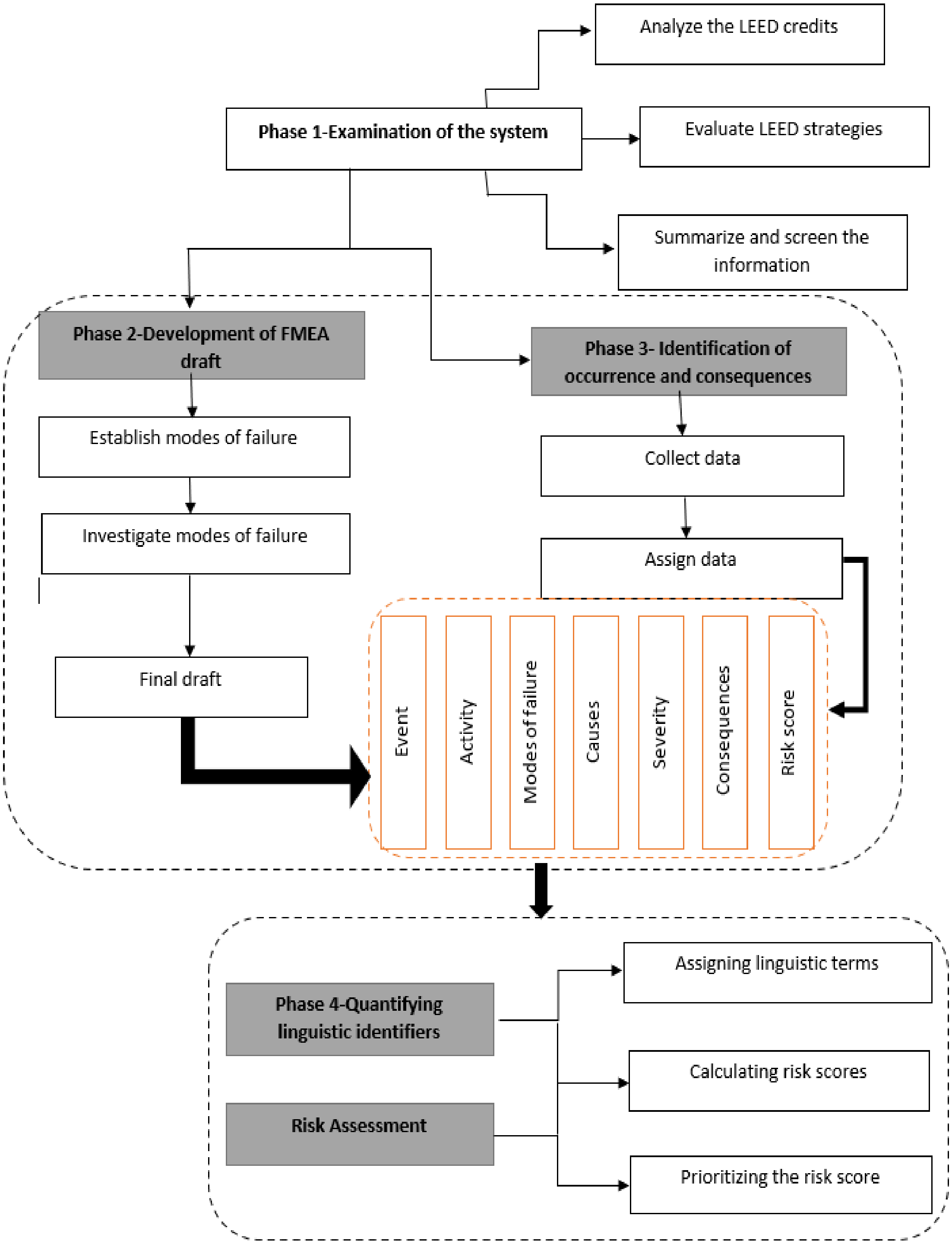

Figure 3-1 Methodology

3.3 Failure Mode Effect Analysis

3.3.1 Phase 1 - System examination

System examinations contributed to system understanding. Before developing an FMEA draft, the system of LEED certification, credit organization, and hazard incidents were thoroughly studied. The following steps were adopted to do the system examination.

i. Analyze the LEED credits individually: The LEED credits were analyzed using published literature and LEED handbooks.
ii. Evaluate the strategies applied to acquire the credit points: The strategies applied were referred to from OSHA reports and LEED handbook.
iii. Summarize different possible circumstances into the system: Based on the collected data from the above two steps, comprehensive data were screened and used for further study.

Table 3-1 shows a summary of the data analyzed and screened after an extensive system examination. The LEED credits analysed in Table 3-1 were based on literature review. However, other LEED credits associated with rating system have stated positive impacts on the safety of workerss , while some LEED credits have mixed impacts. The LEED credits with negative impacts on the health and safety of workers were selectively used in this study. LEED credits like ‘onsite renewable energy’ are achieved through various means such as, wind mills, geothermal, etc. However, this study focuses specifically on PV panel installation. PV electricity is a popular method that has been used for obtaining the LEED credit for renewable energy (Fortunato et al., 2012). PV is suitable in terms of efficiency, maintenance cost, simple installation process for all types of projects (small building to a large complex buildings) (Saleem et al, 2016) . Current statistics shows that the PV panel installation is on high demand for green building projects (Saleem et al, 2016). Similarly, the activities considered for this study for each LEED credit are majorly based on the literature and their popularity in green projects for achieving LEED certification. LEED credits and the related activities are selected depending upon their positive and negative impacts on the workers health and safety from previous literature. The LEED credits with increased safety risk are specifically used in this study. Some exceptions are onsite renewable energy and brownfield redevelopment risk level depends on the strategies implemented on the site. However, the strategies analysed in this study are based on their importance and acceptance by the construction industry.

Table 3-1 Analyzed Data for LEED credits

Sr. No.	LEED Credits	Activities	Identified probable risks
1	Brownfield redevelopment	• Cleaning up contaminated sites by removing contaminants (Wang et al., 2009). • Excavation and trenching (Zhu & Hipel, 2007)	• Exposure to hazardous substances. • Equipment and worker conflicts. • Trenches or excavation may cause fall or collapse.
2	Stormwater quality control	• Construction of retention and detention ponds (trenching and excavation required for the same) (US EPA, 2007)	• Steep slopes of ponds may lead to collapse and fall hazards.
3	Heat island effect roof	• Providing shade by installing solar panels (Fortunato et al., 2012) • Selection of material having low SRI (Kubba et al., 2019) • White roofing instead of black roofing • Vegetating the roof	• Always dangerous to work on roofs causing collapse and falls from heights. • White roofing materials are slippery.
4	Innovative wastewater technologies	• Treating greywater for reuse (Medineckiene et al., 2010) • Use of chemicals (Zhang et al., 2019)	• Exposure to hazardous chemicals.
5	Onsite renewable energy -	• PV panels are connected by cables prone to short circuits (Falvo & Capparella, 2015)	• PV panels are susceptible to fire (Zhao et al., 2018). • PV panel material consists of compounds harmful to human health (Taylor, 2010).

	installation of PV panels	• Installation of PV panels (Kubba et al., 2019)	• Installation on the rooftops poses the risk of fall hazards.
6	Improved commissioning – under pressure work environment	• Commissioning is carried at any possible stage during building construction (Kubba et al., 2019)	• The pressure to perform the tasks precisely ultimately causes falls, conflicts similar to accidents.
7	Construction waste management	• Construction waste contains lead, arsenic, asbestos materials • Use of existing foundations and structures (Kubba et al., 2019).	• Exposure to hazardous materials may cause health problems. • Bacterial infections are possible. • Waste management comprises activities that involve contact with sharp things such as broken pieces of glass or any other injurious materials. • Noise hazard (Cheng & Deng, 2015).
8	Outdoor air delivery monitoring	• Installation of large windows at greater heights (Kubba et al., 2019)	• Fall from heights. • Collapse.
9	Storage and collection of recyclables	• Recyclables collection method (Siddharth et al., 2012) • Segregation (Siddharth et al., 2012).	• Exposure to chemicals. • Contact with sharp-edged bricks stones. • Respiratory problems due to dust.
10	Use of volatile organic compounds.	• Use of low or zero VOC paints, finishing materials (Cincinelli & Martellini, 2017).	• Emission of harmful chemicals. • Reaction with ozone-forming secondary pollutants (Steinemann et al., 2017)
11	Use of reused, recycled. products.	• Use of fly ash bricks (Steinemann et al., 2017)	• Emission of harmful gases.

3.3.2 Phase 2- Development of FMEA

Development of the FMEA sheet involves two major steps:

i. **Establishment of modes of failure**

Modes of failure are derived through system examination. Modes of failure were established by contemplating the strategies used in the LEED credits. Modes of failure were the safety hazards occurring in an event while performing an activity. Hence, event, activity, and modes of failure were categorized in the first step of developing FMEA.

ii. **Investigation of modes of failure**

Systematic data collection and reference standards were responsible for a reliable investigation of failure modes. Modes of failure are investigated to determine the causes of failure. These modes of failure were further investigated to define their risk scores based on linguistic terms.

3.3.3 Phase 3: Determination of occurrence and consequences

This phase constitutes two steps:

1) Collect data: The determination of occurrence and consequence of modes of failure were obtained from published literature.
2) Assign data: A majority of literature included qualitative data (Timofeeva et al., 2018). Hence, qualitative ratings specified in Table 3-2 and Table 3-3 were used to define the probability of occurrence and consequence.

Table 3-2 Linguistic Terms and Scores for Occurrence Probability (Mohammadi et al., 2013)

Occurrence Probability	**Score**	**Description**
Minimum	1	The probability of occurrence is nearly negligible.
Low	2	The chances of occurrence are very low.
Medium	3	Unpredictable situations leading to ultimate risks.
High	4	Consistent and predictable probabilities.
Very High	5	There is a high possibility of risk in this case.

Table 3-3 Linguistic Terms and Scores for Occurrence Probability (Mohammadi et al 2013)

Consequence Severity	**Score**	**Description**
Minimum	1	The effect is negligible on workers' health and safety.
Low	2	In this situation minimal injuries are feasible.
Medium	3	Moderate injuries without life casualties.
High	4	Considerable injuries with long term effect.
Very High	5	Significant injuries with subsequent deaths.

3.3.5 Phase 4: Risk Assessment

The risk assessment in FMEA was achieved using two approaches:

1. Criticality Number calculation (CNC)
2. Risk Priority Number calculation (RPN)

Risk Priority Number (RPN) was used in FMEA to determine the risk level. RPN was defined using Equation 3-1 (Prusek et al., 2017)

$$RPN = P_o \cdot S_c \quad \text{(Equation 3-1)}$$

Where P_o is the probability of occurrence and Sc is the severity of the consequences. RPNs were calculated for each hazard cause and aggregated to determine the risk score for each mode of failure.

This study implements Equation 3-2 for aggregating the total risk of a LEED credit. Therefore, the high risk of any LEED credit was determined by assessing high-risk activity associated with the LEED credit using Equation 3-2.

Risk Score_{max} (activity) = Aggregated risk score (credit)…………… (Equation 3-2).

The maximum risk score method given by Equation 3-2 was used to highlight more on the highest risk value. It provided useful information about the high risk in multi-category hazard system. The high-risk hazard determined the maximum risk that is within tolerance (Bjørnsen & Aven, 2019).

Table 3-4 represents the RPN score range and associated risk description. This explains the severity of the risk of each LEED credit.

Table 3-4 Description for the Risk Priority Numbers

RPN	**Total Risk Description**
1-4	The overall risk score is minimum
5-9	The risk score is low but not negligible
10-14	The risk score is average
15-19	The total risk is substantial
20-25	The risk score is critical

3.4 Results

Table 3-5 presents FMEA for safety risk assessment of LEED credits. Risk scores for each cause are presented. Table 3-5 includes LEED credits, related hazards, and hazard causes. The hazards were further evaluated to present the RPN for each hazard in the table. The linguistic terms assigned to the modes of failure were obtained from multiple literature sources. A contenet analysis was performed. A linguistic term was selected if more than 50% of sources have used the same linguistic term. These linguistic terms were quantified using likert scales presented in Table 3-2 and 3-3

Table 3-5 Failure Mode Effect Analysis

Event	**Activity**	**Modes of Failure**	**Causes**	**Occurrence**	**Consequence**	**RPN**
Brownfield redevelopment	Machines used for excavation	Noise (Timofeeva et al., 2018)	High level of noise due to machines	High (4)	Medium (3)	12
		Conflicts (Shafique, 2019)	Transportation of materials and equipment	High (4)	Medium (3)	12
	Excavation, trenching cleanup	Fall/Collapse (Casanovas et al., 2014)	Sliding of earth/ slippery conditions	Medium (3)	Very high (5)	15
			Moving machines and mechanisms	Medium (3)	Very high (5)	15
		Exposure to hazardous materials (Timofeeva et al., 2018)	Cleaning contaminated sites	Medium (3)	Minimal (1)	3
			Disinfecting sites	Medium (3)	Minimal (1)	3
		Conflicts (Shafique, 2019)	Transportation of materials and equipment	High (4)	Medium (3)	12
Stormwater quality control	Trenching, excavation,	Collapse (Timofeeva et al., 2018)	Trenches and ponds can cause a collapse	Medium (3)	Medium (3)	9

	pond construction	Conflicts (Timofeeva et al., 2018)	Movable equipment and workers	Medium (3)	High (4)	12
Green roof	Vegetated roofs, white roofing	Fall (Casanovas et al., 2014) (Hrica, 2020)	Fall from ladder	Very high (5)	Medium (3)	15
			Fall due to slippery material	Medium (3)	Minimal (1)	3
Innovative wastewater technologies	Greywater treatment, chemical usage	Exposure to hazardous materials (Timofeeva et al., 2018)	Greywater treatment (Maimon et al., 2014)	Medium (3)	Minimal (1)	3
			Contact with harmful substances	Medium (3)	Minimal (1)	3
Onsite renewable energy	Installation of PV panels with electrical cabling	Fall (Casanovas et al., 2014) (Hrica, 2020)	Fall from the ladder	Very high (5)	Medium (3)	15
			Fall from roof	Very high (5)	Very high (5)	25
		Fire breakouts (Timofeeva et al 2018) (Shafique, 2019)	PV panels are susceptible to fire when provided with an electric supply	Medium (3)	Medium (3)	9
		Conflicts (Timofeeva et al., 2018) (Shafique, 2019)	Transporting movables and workers	Medium (3)	Medium (3)	9

	External Wall Insulation	Fire risks	The organic material used in the external wall insulation is susceptible to fires	Medium (3)	Medium (3)	9
		Microbial growth	Formation of Dew points due to cavities (Pukhkal, 2015)	Medium (3)	Low (2)	6
Improved commissioning – under pressure work environment	Supervision at critical construction phases results in work stress disorders (Wang et al., 2017)	Anxiety disorder and obsessive-compulsive disorder, panic	Fall	High (4)	Medium (3)	12
			Conflicts	High (4)	Medium (3)	12
			Fall/ Collapse	Medium (3)	High (4)	12
			Conflicts	Medium (3)	High (4)	12
Construction waste management (Bleck & Wettberg, 2012)	Waste containing harmful materials, reuse	Exposure to hazardous materials (Timofeeva et al 2018)	Contact with harmful emissions	High (4)	Medium (3)	12
			Suffocation	Low (2)	Medium (3)	6
		Conflicts (Shafique, 2019)	Cranes and worker’s conflict	High (4)	Medium (3)	12
			Transportation and workers conflict	High (4)	Medium (3)	12

		Noise	Equipment and Movables	High (4)	Low (2)	8
Outdoor air delivery monitoring	Installation of large windows or panel at heights	Fall (Series & Science, 2018) (Casanovas et al., 2014) (Hrica, 2020)	Fall from a ladder	Very high (5)	Medium (3)	15
			Fall from scaffolding	Very high (5)	High (4)	20
Storage and collection of recyclables	Collection and segregation methods	Exposure to hazardous materials (Adams et al., 2016)	Fly ash bricks expose heavy metals with toxic properties	Medium (3)	Low (2)	6
Indoor Air Quality	1.Use of volatile organic compounds 2.Use of reused, recycled. 3.Products Installation of air cleaning equipment	Emission of harmful chemicals (Timofeeva et al 2018)	Air cleaners produce toxic chemicals during the process	Low (2)	Low (2)	4
	4. Use of organic materials or compounds	Microbial growth (Exposure to hazardous materials)(Adams et al., 2016)	Exposure to mold spores	Medium (3)	Minimal (1)	3

3.5 Rank LEED credits based on the level of risk

Table 3-6 provides the LEED credit ranks based on the risk score calculated in the Failure Mode Effect Analysis. ‘Onsite renewable energy’ ranked first with the highest risk score of 25. However, ‘innovative wastewater technologies’ ranked lowest in terms of the risk score.

Table 3-6 Failure mode effect analysis

Sr. No	LEED Credits	Risk score	Risk rank
1	Onsite renewable energy	25	1
2	Brownfield redevelopment	15	2
3	Heat Island effect	15	2
4	Outdoor air delivery monitoring	15	2
5	Stormwater quality control	12	3
6	Construction waste management	12	3
7	Storage and collection and recyclables or impact reduction	6	4
8	Indoor air quality	4	5
9	Innovative wastewater technologies	3	6

3.4.1 Validation of results

FMEA results were validated using published literature. Mulhern (2008) revealed that construction workers are exposed to safety while working on the rooftops for acquiring the LEED credits for, vegetated roofs and onsite renewable energy. Mulhern (2008) emphasized difficulties faced by workers and contractors while working on heights with the new materials that are not familiar to them. In a case study of a university green building in USA, a higher rate of injuries were observed while performing waste management activities such as collection, segregation, and dumping activities (Terwoert and Ustailieva, 2013).

Detailed case studies were performed by Mulhern (2008); Karakhan and Gambatese (2017); Fortunato et al., (2012) to evaluate the risks related to LEED credits. However, these case studies do not clearly indicate activities associated with LEED credits nor causality.

These studies revealed that increased safety risks are associated with LEED credits for stormwater quality control, onsite renewable energy, innovative wastewater technologies, heat island roof effect, construction waste management, outdoor air delivery monitoring, and the use of low emitting materials (Karakhan, 2016). Moreover, the abovecase studies only revealed the comparative increases and decreases in safety hazards related to these LEED credits (Fortunato et al., 2012). Risk rankings of ‘onsite renewable energy’, ‘construction waste management’ ‘sustainable sites’ in Dewlaney and Hallowell (2012) are consistant with the FMEA. Karakhan and Gambatese, (2017) quantified negative and positive occupational health and safety impacts of the construction industry. This study used previous literature to quantify safety impacts. This analysis examined the positive and negative impacts of LEED credits on occupational health and safety. The high-risk LEED credits identified in this research are consistant with risks identified by Karakhan and Gambatese, (2017)

3.6 Summary

This chapter illustrated a systematic analysis of the LEED rating system on workers’ health and safety impact. This chapter performed a detailed analysis of the safety failures, effects, probabilities, and consequences of opting for LEED credits. The FMEA method was used to calculate the risk score for each LEED credit. The results revealed that installing PV panels on the rooftops involves the highest safety risk.

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CHAPTER 4

CASE STUDY FOR COST BENEFITS AND SAFETY HAZARD OPTIMIZATION

4.1 Introduction

LEED certification has been the most popular building rating system. However, clients are often concerned about the incremental cost required to achieve the LEED credits (Abdallah et al., 2016). The additional construction cost for gold and platinum buildings were found to be 7.43% and 9.43% of the total cost of the construction (Latif et al., 2018.). On the other hand, the rate of injury in LEED-certified buildings has been higher than in traditional construction (Karakhan et al., 2016). It is important to minimize the cost and injury rate in LEED construction.

Green buildings aim to be cost-efficient while little evidence has been found that buildings consume extra costs to get LEED-certified (Latif et al., 2018). As the level of certification steps up, the cost of building gradually increases, and the efforts to acquire the LEED points also increase. Efforts are being made to reduce the cost without compromising the LEED certification level (Akcay & Arditi, 2017). Worker safety could be an important factor in this decision (Abdallah et al., 2016). While ensuring workers' safety, the cost-effectiveness of the replaceable options must be assessed. This chapter performed a case study that optimized cost and workers safety in LEED construction.

Particle Swarm Optimization (PSO), Genetic Algorithm (GA) methods are available for optimization. A Multi-Objective Optimization (MOO) was used because it does not require complex equations for achieving optimal solutions. (Gunantara, 2018). Initially, the problem was classified to decide the objectives and constraints. A preliminary list of solutions was developed based on the case study. Finally, a set of solutions were plotted on a graph to draw a Pareto frontier passing through the efficient combinations, also known as Pareto optimal solutions.

This study was intended to minimize the additional cost required to achieve LEED credits while reducing the safety risks to achieve points calculated for gold certification. Multi-Objective Optimization (MOO) was incorporated to achieve the objective mentioned above. A case study was conducted to determine the LEED credit combination for minimum cost and safety risk.

4.2 Methodology

The MOO method is extensively used by many disciplines of engineering, medical, and finance sectors. It allowes reducing the complexities involved in selecting the best suitable options for any procedure (Marler & Arora, 2010). Choosing optimal solutions to minimize the safety hazards on the construction site was difficult, irrespective of the knowledge and experience of the safety manager (Eslami Baladeh et al., 2019). MOO gives several better solutions instead of a single best solution.

MOO can be mathematically represented as,

Min/max $f_1(x)$, $f_2(x)$………. fn(x)

Subjected to x € U………………………….(Equation 4.1) (Gunantara, 2018).

Where f_n is the n^{th} objective function, x is the solution and U is a feasible solution set

4.2.1 Pareto method of optimization

Vilfredo Pareto introduced the MOO method to identify optimal solutions for more than one objective. The Pareto method is used to determine the optimal solution when the solutions and the constraint are different (Gunantara, 2018).

Figure 4-1 depicts a graphical representation of the Pareto Optimal solution. Solution B and C are non-dominated optimal solutions represented on the Pareto front. Function f1 and f2 are presented as minimizing functions.

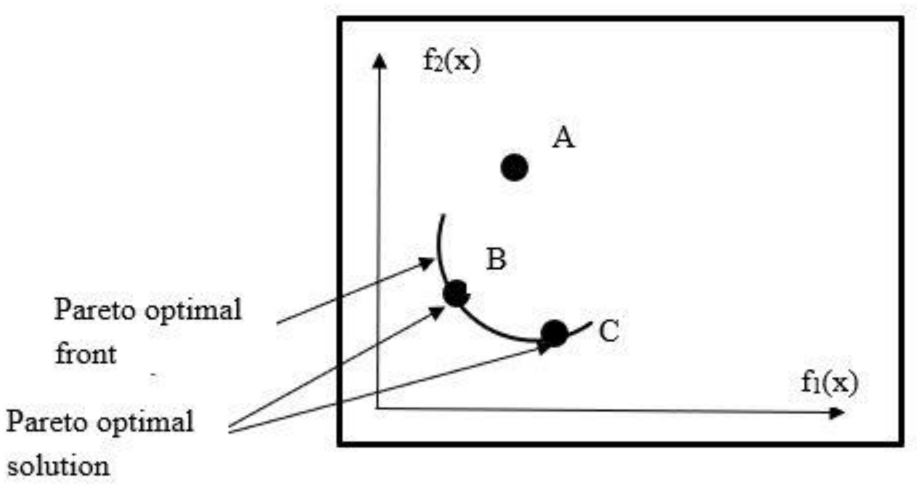

Figure 4-1 Graphical depiction of Pareto Optimal Solution

Pareto-based MOO can be given by following equation,

$f_{1,opt} = \min f_1(x)$

$f_{2,opt} = \min f_2(x)$.......................................(Equation 4-2) (Gunantara, 2018)

Given the constraint function $g_j(x)$ > or equal to 0 (Chen et al., 2019).

The Pareto optimization method requires a set of optimal solutions that are developed as combinations. The set of solutions was based on the objectives and constraints derived from the problem statement. These optimal solutions were then plotted on a graph to draw a Pareto frontier and obtain the optimal solution among the combinations.

4.3 Case study

The case study aimed to study the scenario-based credit point calculations and their effect on the safety and cost of the project. This case study was further used for optimization. In this case study, the building was assumed to be at the predesigning stage. Approximate points were calculated under each category based on primary assumptions. The LEED credits were calculated such that the final points were within a range of 60-79. This range certified the building with gold certification. Risk causing credits were not eliminated initially.

Centre for Engineering Innovation (CEI)is an institutional building situated in Windsor, Ontario, Canada. The assumptions made for the point calculation were based on the location of the building. The building is an educational building that is spread over 28,800 square meters.Transit locations, bus stops, parking sites, and restaurants were counted on for point estimation. Points for energy efficiency and water efficiency were assumed in the percentage given in the LEED handbook.

Figure 4-2 Illustrates the Revit model of the CEI building.

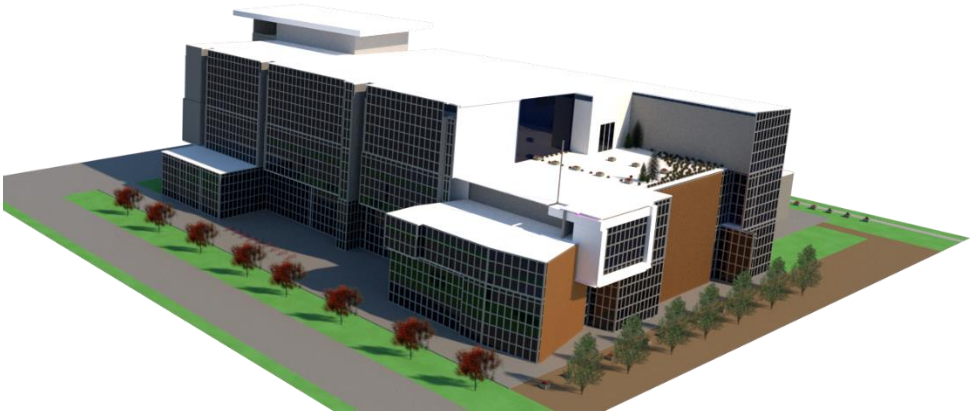

Figure 4-2 BIM Model of CEI

Table 4-1 is an evaluation of the LEED points obtained by the building. This is a point evaluation table provided with points achieved in different categories of the LEED certification system.

Table 4-1 Point calculation for CEI building

Category and maximum points	**Maximum points**	**Points Obtained**
Location and transportation – 15	15	8
Sustainable sites – 10	10	6
Water efficiency – 12	12	10
Energy and atmosphere – 31	31	22
Material and resources – 13	13	10
Indoor Environmental quality – 16	16	10
Total points = 66		

The E.D. Lumley Centre for Engineering Innovation was expected to get GOLD Certification from USGBC under the LEED certification system. However, further analysis was done to find out the effect of point calculation if the risk-posing activities are eliminated or replaced by other available options.

4.4 Incremental Cost of LEED Credits

The unit costs were found from the RSMeans. RSMeans is a popular resource for cost estimation published by Gordian. The estimated cost also included the cost of transportation and labour as per the requirements. No taxes or additional fees for supervision, design, and architecture were added. Table 4.2 presents risk scores obtained from FMEA and the incremental costs calculated from RSMeans.

By eliminating or replacing the credits causing safety hazard building can achieve SILVER certification as shown in Table 4-2.

Table 4-2 Safety Hazard Elimination and its Effect on Credit Point Calculations

Risk-posing Credit	**Risk score from FMEA**	**The incremental cost for CEI based on RS Means ($)**	**Replacement or Elimination**
Brownfield redevelopment	15	27550	Historic district or Priority designated land
Stormwater quality control	12	31000	Green infrastructure
Heat Island effect	15	22700	Non-roof measures
Innovative wastewater technologies	3	49000	Low flow fixtures, waterless urinals
Onsite renewable energy	25	60100	N/A
Construction waste management	12	N/A	N/A
Storage and collection of recyclables or impact reduction	6	N/A	N/A
Outdoor air delivery monitoring	15	49600	Enhanced IAQ strategies
Indoor air quality	4	39500	Partially applicable
Total points after elimination or replacement = 53			

4.5 Pareto Optimization

4.5.1 Step 1 – Classify the problem

The objective of the analysis was to propose combinations of LEED credits that can give gold certification to the building with the lowest safety impact at the lowest incremental cost. The best combination should be chosen to achieve the desired certification level. The order of objectives is given irrespective of the importance. These objectives are of equal importance while performing MOO.

Objective 1 – Minimising the total cost

Objective 2 – Minimising the total risk score

Constraint – Credit points to be in the range of (60-79)

4.5.2 Step 2 - Develop a preliminary list of solutions

A set of solutions was required to achieve the above-mentioned objectives. The set of the solution developed should not compromise any of the objective functions while attaining the goal (Eslami Baladeh et al., 2019). The total cost and risk were calculated from Table 4-4 at the end. The following combinations were developed with the reference of Table 4-3. Only high-risk LEED credits were used to develop the combination. All other LEED credits with no risks were kept constant in the total calculation. The credit points are added or subtracted from the total points obtained in Table 4-2. Out of the total points calculated in Table 4-2, 49 points are constant. These credit points were obtained by the low-risk LEED credits. These low-risk credits were not considered in the study related to a safety hazard in Chapter 2. Therefore, the points for each combination were to be added to 49. Table 4-3 to Table 4-12 illustrate solutions sets to achieve as many points required for LEED gold certification. These tables contain credit point calculations, total risk calculation, and the total incremental cost calculation.

Table 4-3 Combination A

Risk-posing Credit	**Points**	**Risk score from FMEA**	**The incremental cost for CEI based on RS Means**
Brownfield redevelopment	3	15	$27,550
Stormwater quality control	3	12	$31,000
Heat Island effect	2	15	$22,700
Innovative wastewater technologies	5	3	$49,000
Onsite renewable energy	3	25	$60,100
Outdoor air delivery monitoring	2	15	$49,600
Indoor air quality	3	4	$39,500
Total	21	89	$279,450
Total points obtained = 49 + 21 = 70 (Gold)			

Table 4-4 Combination B

Risk-posing Credit	**Points**	**Risk score from FMEA**	**The incremental cost for CEI based on RS Means**
Stormwater quality control	3	12	$31,000
Heat Island effect	2	15	$22,700
Innovative wastewater technologies	5	3	$49,000
Onsite renewable energy	3	25	$60,100
Outdoor air delivery monitoring	2	15	$49,600
Indoor air quality	3	4	$39,500
Total	18	74	$251,900
Total points obtained = 49 + 18 = 67 (Gold)			

Table 4-5 Combination C

Risk-posing Credit	**Points**	**Risk score from FMEA**	**The incremental cost for CEI based on RS Means**
Brownfield redevelopment	3	15	$27,550
Stormwater quality control	3	12	$31,000
Innovative wastewater technologies	5	3	$49,000
Onsite renewable energy	3	25	$60,100
Indoor air quality	3	4	$39,500
Total	17	59	$207,150
Total points obtained = 49 + 17 = 66 (Gold)			

Table 4-6 Combination D

Risk-posing Credit	**Points**	**Risk score from FMEA**	**The incremental cost for CEI based on RS Means**
Stormwater quality control	3	12	$31,000
Heat Island effect	2	15	$22,700
Innovative wastewater tech.	5	3	$49,000
Onsite renewable energy	3	25	$60,100
Brownfield redevelopment	3	15	$27,550
Indoor air quality	3	4	$39,500
Total	19	74	$229,850
Total points obtained = 49 + 19 = 68 (Gold)			

Table 4-7 Combination E

Risk-posing Credit	**Points**	**Risk score from FMEA**	**The incremental cost for CEI based on RS Means**
Stormwater quality control	3	12	$31,000
Innovative wastewater technologies	5	3	$49,000
Onsite renewable energy	3	25	$60,100
Indoor air quality	3	4	$39,500
Total	14	44	$179,600
Total points obtained = 49 + 14 = 63 (Gold)			

Table 4-8 Combination F

Risk-posing Credit	**Points**	**Risk score from FMEA**	**The incremental cost for CEI based on RS Means**
Stormwater quality control	3	12	$31,000
Heat Island effect	2	15	$22,700
Innovative wastewater technologies	5	3	$49,000
Onsite renewable energy	3	25	$60,100
Indoor air quality	3	4	$39,500
Total	16	59	v202,300
Total points obtained = 49 + 16 = 65 (Gold)			

Table 4-9 Combination G

Risk-posing Credit	**Points**	**Risk score from FMEA**	**The incremental cost for CEI based on RS Means**
Innovative wastewater technologies	5	3	$49,000
Onsite renewable energy	3	25	$60,100
Outdoor air delivery monitoring	2	15	49,600
Indoor air quality	3	4	$39,500
Total	13	47	$198,200
Total points obtained = 49 + 13 = 62 (Gold)			

Table 4-10 Combination H

Risk-posing Credit	**Points**	**Risk score from FMEA**	**The incremental cost for CEI based on RS Means**
Brownfield redevelopment	3	15	$27,550
Stormwater quality control	3	12	$31,000
Onsite renewable energy	3	25	$60,100
Indoor air quality	3	4	$39,500
Total	12	56	$158,150
Total points obtained = 49 + 12 = 61 (Gold)			

Table 4-11 Combination I

Risk-posing Credit	**Points**	**Risk score from FMEA**	**The incremental cost for CEI based on RS Means**
Stormwater quality control	3	12	$31,000
Innovative wastewater technologies	5	3	$49,000
Onsite renewable energy	3	25	$60,100
Outdoor air delivery monitoring	2	15	$49,600
Total	13	55	$189,700
Total points obtained = 49 + 13 = 62 (Gold)			

Table 4-12 Combination J

Risk-posing Credit	**Points**	**Risk score from FMEA**	**The incremental cost for CEI based on RS Means**
Brownfield redevelopment	3	15	$27,550
Stormwater quality control	3	12	$31,000
Heat Island effect	2	15	$22,700
Onsite renewable energy	3	25	$60,100
Indoor air quality	3	4	$39,500
Total	15	71	$180,850
Total points obtained = 49 + 15 = 64 (Gold)			

4.4.3 Step 3 - Obtaining an optimal set of solutions

Table 4-13 exhibits a set of solutions obtained from the above combination. These solutions will be plotted on a graph to determine the most efficient optimal solutions. The table contains total risk and total incremental cost for each combination. Table 4-13 presents optimal solutions with their total risk scores and total incremental cost.

Table 4-13 Optimal Solution for Combinations

Combination	Total Risk Score	Total Incremental Cost
A	84	$279,450
B	79	$251,900
C	54	$207,150
D	74	$229,850
E	44	$179,600
F	59	$202,300
G	47	$198,200
H	56	$158,150
I	55	$189,700
J	71	$180,850

Figure 4-3 is the scatter graph with the total risk score on X-axis and incremental cost on Y-axis. The combinations from A to J are plotted on both the axes. A pareto frontier is drawn to mark the most effective combination to achieve Gold certification with minimum risk and minimum incremental cost.

The location of pareto front depends upon the objective functions of the problem. In this study, objective functions were subjected to minimization. Therefore, the the pareto front passes along the optimal solutions with minimum values. The combinations closer to the pareto front are the most efficient optimal solutions and those away from the pareto front are the least efficient combinations as shown in Figure 4-3.

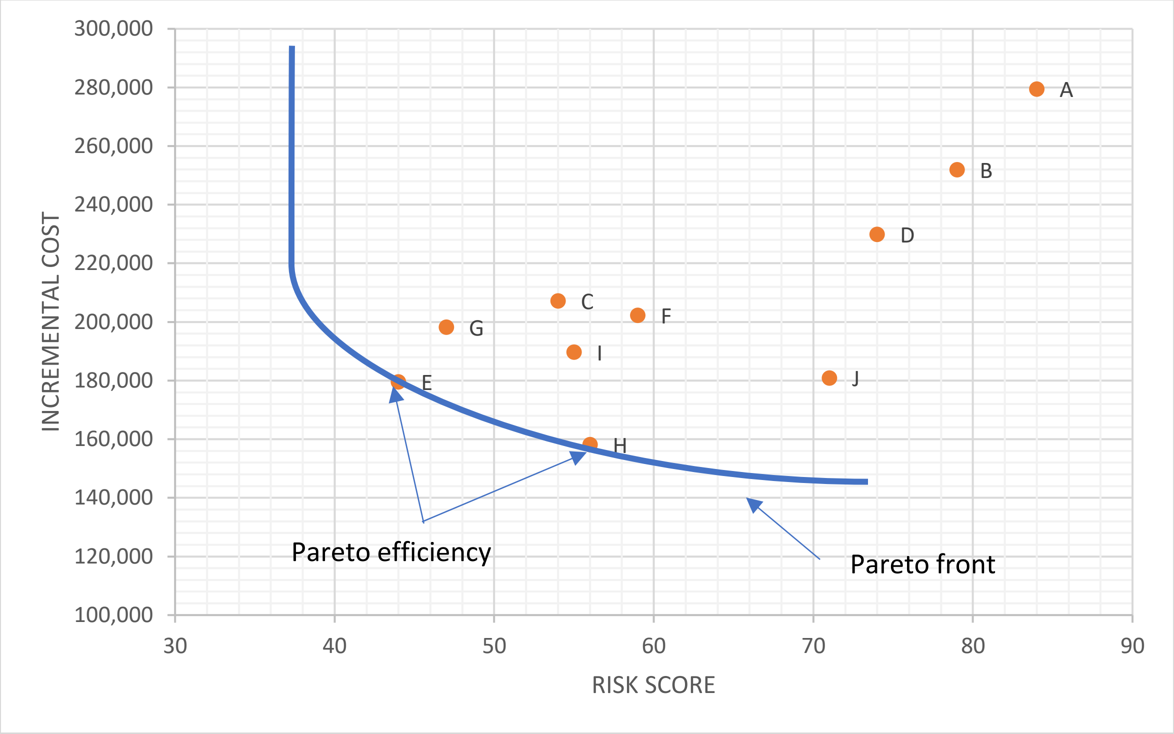

Figure 4-3 Graphical presentation of Pareto optimal solutions

From Figure 4-3 Optimal solutions on the Pareto front can be determined. Combination E and H were non-dominated optimal solutions, whereas other solutions are dominated. Combination E had a minimum risk level but has incremental costs greater than H, while combination H comprised the lowest cost while the risk is higher. Other solutions were dominated by both the axes and hence cannot be the most efficient Pareto optimal solutions. Hence, E and H combinations can be recommended as an optimal solution satisfying both the objectives.

However, further interpretation of the above results was made by opting the most efficient optimal solution between combination E and H. Combination E depicts lower risk score and higher implementation cost whereas, combination H presents higher risk score and a lower implementation cost from Table 4-11. Final decision can be made by the practitioners by comparing the risk score and the implementation cost of combination E and H. From a construction management point of view, selecting a combination with lower risk to the workers will be preferred. Therefore, combination E will be the final optimal solution that can be opted and executed.

4.5 Summary

In this chapter, the optimal LEED credit combination to achieve LEED gold certification was determined by using MOO. Results of FMEA and RS means cost data were used. Pareto optimization was used to determine the optimal LEED credit combination that achieves the LEED gold certification. The optimal LEED credit combination that has the lowest safety risk and incremental cost includes stormwater quality control, heat island effect, innovative wastewater technologies, innovative wastewater technologies, onsite renewable energy, and indoor air quality.

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CHAPTER 5

DYNAMIC RISK ANALYSIS USING BAYESIAN BELIEF NETWORK

5.1 Introduction

Bayesian networks have been used in construction safety and risk analysis to assess the potential causes and effects (Chan et al., 2020). A systematic risk analysis using computational interdependencies must be followed to prevent occupational hazards (Leu & Chang, 2013). A Bayesian network can be effectively demonstrated to compute the effects of a specific incident while performing occupational safety management (Sarkar et al., 2017). A Bayesian network is a feasible method for analyzing the safety risk or hazard probability of a construction project, as it can infer probabilities of a given scenario based on a set of variables. The model can be upgraded easily for every changing parameter and hence the scenario.

Previous researchers have conducted surveys to identify the relationship between safety factors and safety performance. Factors affecting safety performance are direct and indirect (Chan et al., 2020). There exists a logical relationship among these parameters that impacts the overall safety of a project. Several factors are responsible for any accident occurring on site. However, a single factor is responsible for multiple hazards (Sarkar et al., 2017). Therefore, construction project safety changes with changing factors or project parameters. This study used the parameters related to activities involved to implement LEED credits.

Decision trees, fuzzy rule-based models, fuzzy cognitive models, and bayesian networks are some methods used for predictive risk assessment (Ismail et al., 2011). This research implemented Bayesian network analysis because it constitutes a valid technique for creating inferences. It prioritizes the hazards related to LEED credits to achieve the performance objectives of a project. The Bayesian network in this study creates inferences for different scenarios to analyze the impact of project parameters. The graphical interrelationship presented in this research can be understood using Bayesian network analysis.

This chapter presented the probabilities of hazard assessment to examine the impact of project parameters on the safety risk of LEED credits. The probabilities of safety hazards were determined based on conditional dependencies of a set of variables. A scenario-based analysis was conducted to determine the LEED credits with high safety hazards based on varying project parameters.

5.2 Bayesian Networks

Bayesian networks were designed to derive results in the form of conclusions concerning probabilistic relationships based on available information. These probabilistic variables were developed for the set of variables to deliver reasoning for the network provided (Chan et al., 2020). It provided solutions to complex problems, in particular, developing a relationship between risk and its predictive variables. This is also known as the multivariate probabilistic inference method (Vieira et al., 2017). Bayes theorem was also called Bayes law. It can be stated as

$$P(O/A) = \frac{P(A/O)P(O)}{P(A)} \qquad \text{(Equation 5-1) (Vieira et al., 2017)}$$

Equation 5-1 gives the probability of an event O given that A occurs represented as $P(O/A)$. Similarly, $P(A/O)$ represents the probability of event A while the event O is known. $P(A)$ and $P(O)$ are two independent probabilities of occurrence. Bayesian networks have a quantitative and quantitative unit. The qualitative part refers to directed acyclic graphs that were represented based on available data and information. The quantitative part refers to a conditional probability distribution (Vieira et al., 2017). BN can be illustrated as BN = <G, Θ>, where G is the Directed Acyclic Graph whose nodes X1, X2, ..., Xn represent random variables, and Θ is the set of quantitative parameters of the network (Anezeris et al., 2013).

Figure 5-1 represents the basic structure of a directed acyclic graph. The direction of arrows move from a child node to the parent node.

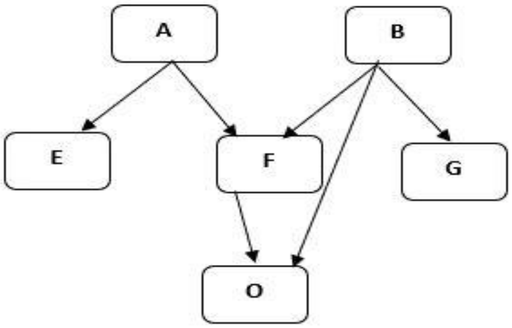

Figure 5-1 An example of the acyclic diagram

5.3 Bayesian network applications in the construction safety analysis

Bayesian networks were gaining popularity for safety analysis in various fields of study. Safety risk analysis for electrical and mechanical works was performed using a Bayesian network. The method was applied to repair, maintenance, alteration, and addition works (Chan et al., 2020). Bayesian networks were also applied in fall risk analysis in bridge construction projects (Chen & Wang, 2017). A similar approach was used by Sarkar et al. (2017) to analyze occupational safety hazards in the steel industry. Fall hazards in steel construction projects were examined using Bayesian networks (Leu & Chang, 2013). The severity of accidents was tested by Vieira et al. (2017) in the construction industry. It was implemented in different areas of the building, including life cycle analysis, sensitivity analysis, and spatial analysis (Tian et al., 2018). Moreover, Bayesian network analysis was applied to workers' health and safety management to analyze predictions, severity, and effects (Hnho et al., 2018). The Bayesian network was also applied to analyze traffic accidents on the rural highways of Spain (De Oña et al., 2011). However, the current literature does not show any evidence of BN application to analyze safety hazards associated with LEED credit or green building.

5.4 Methodology

This chapter evaluated high-risk LEED credits to determine their potential causes and effects and the interdependency of the factors causing safety hazards. There were three vital steps involved in this analysis: (1) data collection and data processing, (2) constructing acyclic diagrams, and (3) performing Bayesian network analysis in Netica. Phase 1 involves principal factor extraction and attribute selection.

These factors were causes and sub-causes, which were screened from an extensive literature review. The attributes were selected for each factor, which is further explained in the upcoming sections. In phase 2, principal factors were arranged in the order of top events, intermediate events, and base events. Acyclic diagrams were then represented using the pre-determined events. Construction, evaluation, and analysis of the Bayesian networks were performed in phase 3 of this chapter. Figure 5.2 illustrates the methodological approach of this chapter. Furthermore, these steps are explained in detail throughout the chapter.

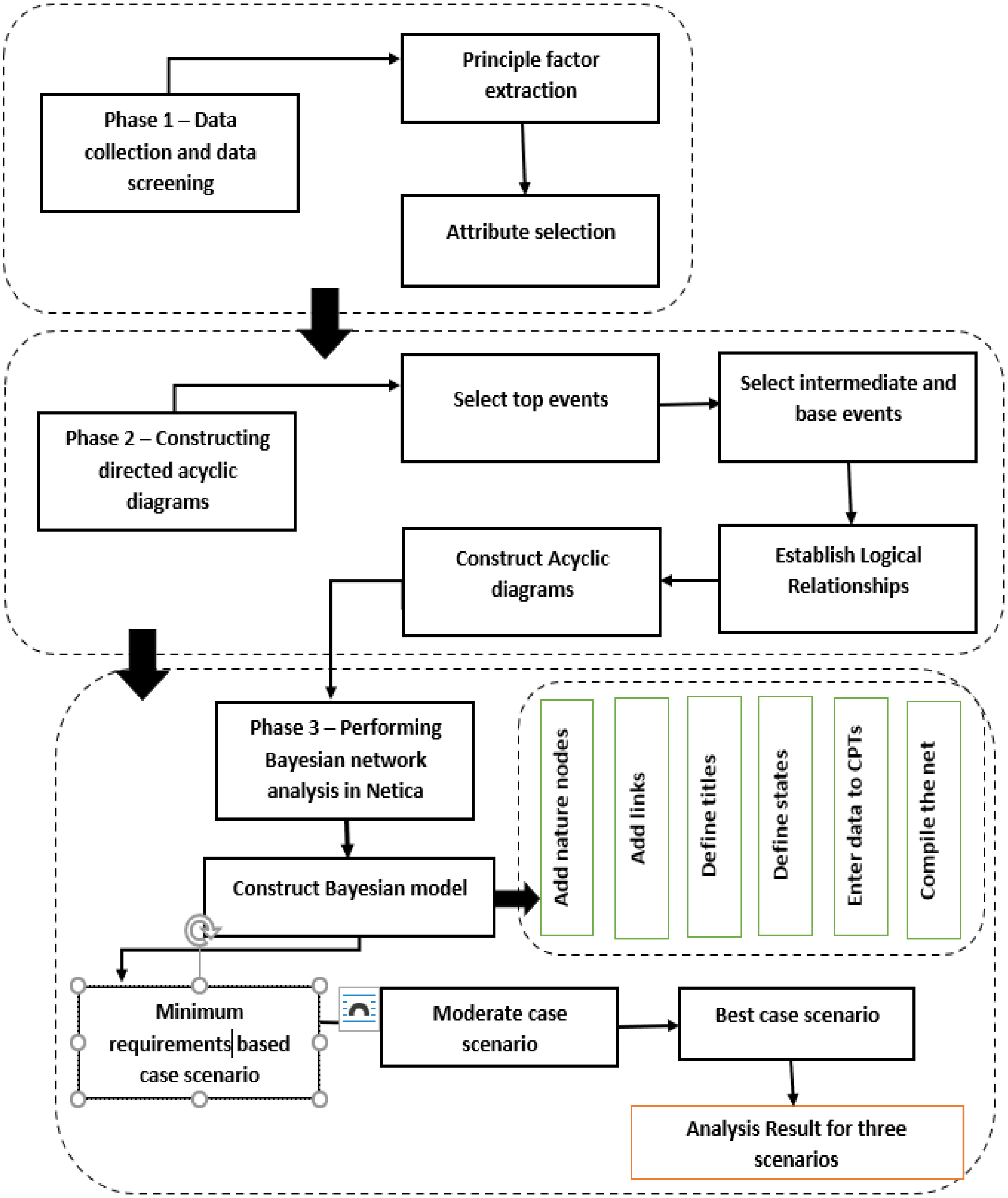

Figure 5-2 Methodology

5.5 Phase 1 Data collection and data processing

Data collection and processing involves two major parts.

5.5.1 Data collection for principal factor extraction

Initially, journals and research articles related to safety assessment were used to decide the factors and attributes of Bayesian networks. The preliminary factors were taken from the Failure Mode Effect Analysis chapter. These involve mainly the basic causes. Further event extraction was done with the help of published literature.

Accumulated data was then processed to prioritize the sequence of top event, intermediate event, and the bottom event. These events were represented in a top-down manner. The top event was the safety hazard associated with the LEED credit. The intermediate and bottom events were speculated as causes and sub-causes. The sub-causes were screened to depict the most common and relevant factors for this study. Tables were created for all the safety hazards identified in previous chapters. The top events were categorized as A1 while the intermediate and bottom events fall sequentially.

Safety inspection and supervision, working experience, and safety training were the most influential factors according to Cronbach's α for safety factors (Chan et al., 2020). These factors were termed as indirect causes and are conveniently used for the acyclic diagrams. Table 5-1 to Table 5-5 present the direct and indirect causes associated with the LEED hazard.

Table 5-1 Causes related to Fall Accidents

A1	Fall – Brownfield redevelopment	C1	Fall from roof
A2	Fall – Onsite renewable energy	C2	Fall from ladder
A3	Fall – Indoor air quality	C3	Fall from scaffolding
B1	Fall from excavated edges	D1	Slippery conditions
B2	Fall on/from trenches	D2	Safety guidelines
B3	Fall due to PV panel installation	D3	Experience/ skill of a worker
B4	Fall due to door window installation	D4	Equipment condition

Table 5-2 Causes related to Collisions or conflicts

A1	Collision–Brownfield redevelopment	C3	Stuck by falling from moving object
A2	Collision – Onsite renewable energy	C4	Caught in between objects
A3	Collision – Construction waste management	D1	Poor management
B1	Transportation, cranes, equipment	D2	Insufficient safety training
C1	Struck by object - equipment	D3	Ineffective sign warnings
C2	Struck by a falling object		

Table 5-3 Causes Related to Exposure to Hazardous Material

A1	Brownfield redevelopment	B4	Use of organic materials
A2	Wastewater treatment	C1	Toxic material exposure
A3	Indoor air quality	C2	Dust suffocation
A4	Use of recyclables	C3	Heavy metal exposure
B1	Cleaning up contaminated sites	D1	Insufficient exposure monitoring
B2	Segregation and collection of construction waste	D2	Insufficient evacuation facilities
B3	Greywater treatment	D3	Sign warnings

Table 5-4 Causes Related to High Noise

A1	Brownfield redevelopment	C1	Heavy material transportation
A2	Construction waste management	C2	High noise machinery
B1	Excavating machinery	D1	Noise barriers
B2	Demolition machinery	D2	Lack of maintenance
B3	Transporting vehicles, cranes	D3	Lack of inspection

Table 5-5 Causes Related to Fire Explosions

A1	Onsite renewable energy	C2	Explosions
A2	Construction waste management	B1	Dust explosions
B3	Fire due to electrical glitch	B2	Demolition blasting
D1	Improper inspection	D2	Inefficient sign warnings
D3	Lack of safety equipment	D4	Ineffective control mechanism

5.5.2 Selection of attributes

The attributes were selected based on the FMEA and the questionnaire surveys obtained from published articles. The attributes are specifically related to LEED construction. Additional attributes were selected based on similar studies. Each selected attribute had two responses, except for the top events.

5.5.3 Data collection for assigning the probabilistic values in the network

The data collected for this study refers to more than one source. The nucleus data was collected from a well-known source, Occupational Safety and Health Administration (OSHA). The numerical data collected from these sources was processed to convert it into cumulative percentages. The granular data inferences were made from published articles based on simplified scales. Moreover, similar studies involving questionnaires and surveys were addressed for data accountability.

After accumulating the required data, the data cells were entered with probabilistic and deterministic entries. The percentage probabilities of the base events are taken from the numerical dataset extracted from the U.S. Bureau of Labor Statistics, 2018. To calculate the percentage probabilities, total fatalities in each category are determined. Then the percentage hazard for each subcategory was calculated based on the total number of fatalities. For the deterministic approach, the percentage scales were used based on data available in the current literature.

5.6. Directed Acyclic Diagrams

A directed acyclic diagram was constructed by selecting top events, intermediate events, and base events. Interdependencies and relationships were established among the selected event to form a complete acyclic diagram. The interrelationships were developed based on the published literature. Some of the events selected for this study were screened based on their relevance to the LEED credits and related activities.

Figure 5.3 illustrates the combined acyclic diagram for the safety hazards related to LEED credits. It represents the relationship between the causes and sub-causes impacting the project parameters.

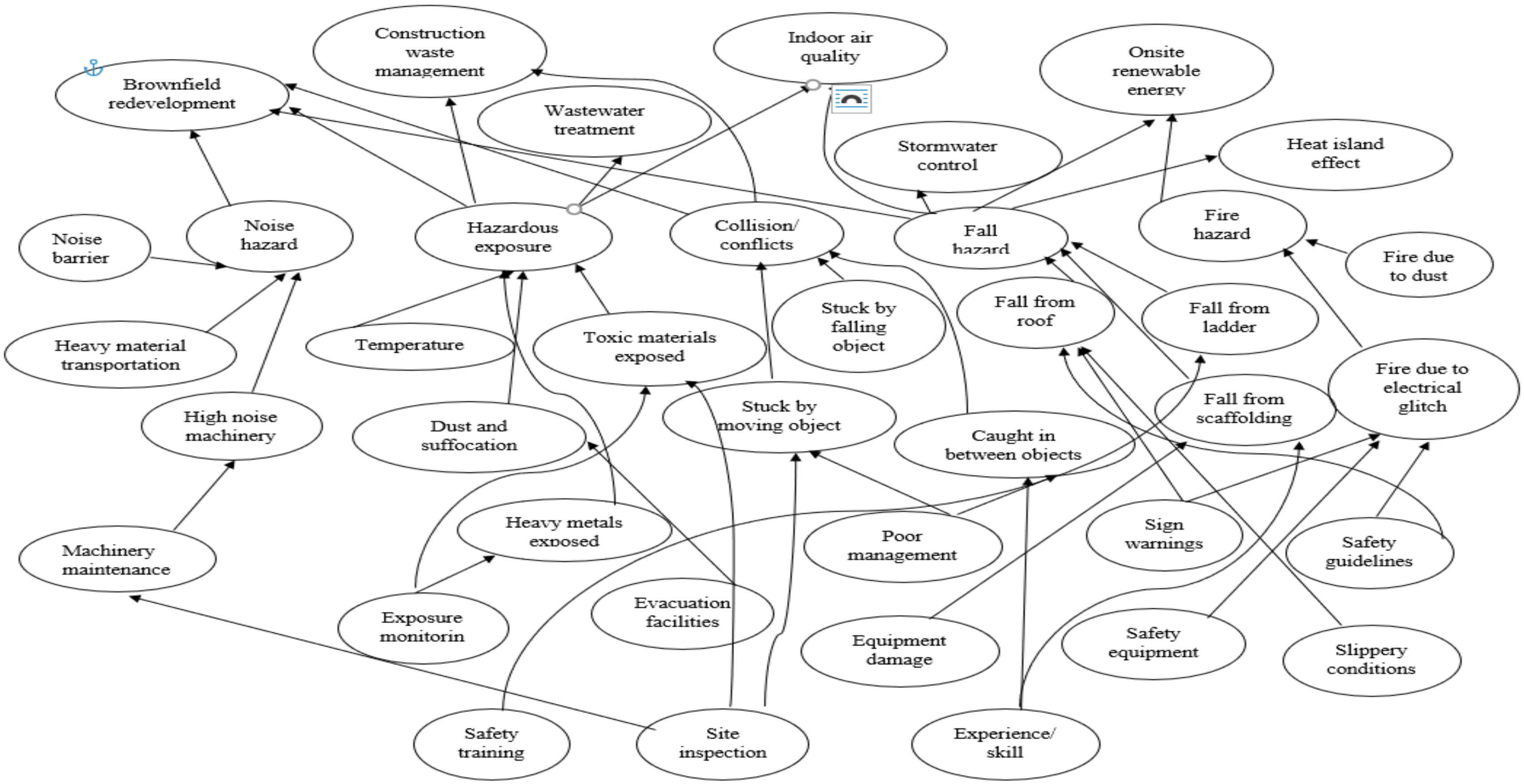

Figure 5-3 Combined acyclic diagram for hazards associated with high-risk LEED credits

5.6.1 Converting acyclic diagrams to Bayesian network

The acyclic diagrams were used to construct Bayesian networks and compute conditional probabilities. These diagrams helped to build the networks based on relationships and interdependencies illustrated by acyclic diagrams. The acyclic diagrams were combined to form one complete Bayesian network to examine the LEED credit hazard based on project parameters.

5.6.2 Bayesian network analysis in Netica

The BN was demonstrated in Netica, which is a product of Norsy's Software Corporation. The benefit of this software is that it can be updated when a new set of data is available (Kabir et al., 2015). The algorithmic approach used by this software was useful for generating the likelihoods, and minimum and maximum probabilities of the given parameter. It also generated results from an incomplete dataset (Pollino & Henderson, 2010).

Netica was selected for this analysis because it can generate results for any desired input. It can compile heavy and complicated nets. The data limitations of this research area can be overcome by using Netica with minimum inconsistencies. Figure 5-7 is a Bayesian network model for LEED credits and associated hazards. The Bayesian network consisted of child nodes that were connected to the parent nodes. The relationships and interdependencies are established based on the individual acyclic diagrams that were drawn using the tabulated data with causes and sub causes. Similar examples of networks were observThe data entered for compilation consists of both the deterministic and the probabilistic approach. These datasets were depicted in the form of conditional probability tables. Conditional probability tables are the probabilities stated in a table based on different conditions of nodes (Chan et al., 2020)**.** Scenario analysis was performed by changing the values of the child nodes.

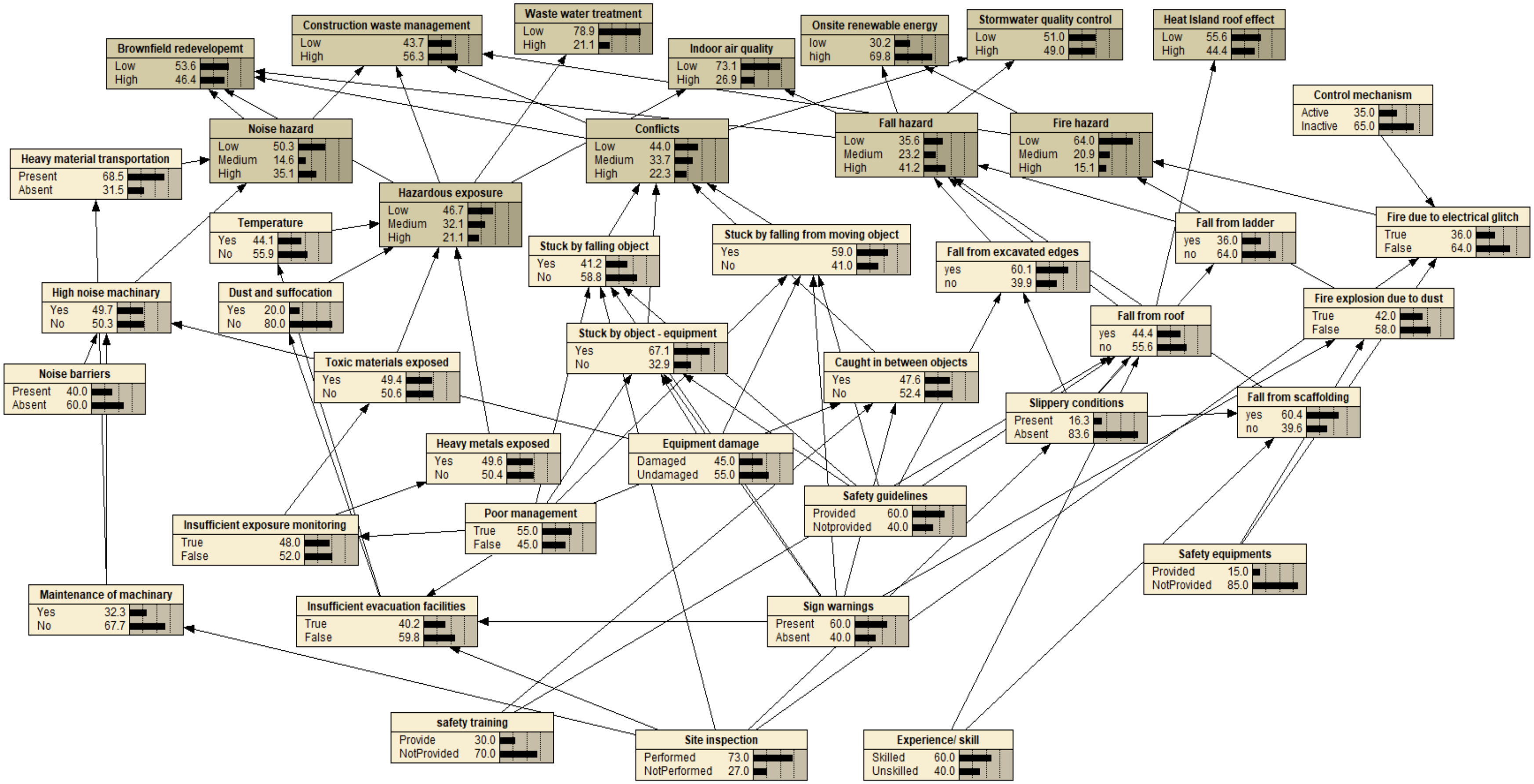

Figure 5-4 Bayesian Network Model

5.7 Scenario Analysis

The BBN network modeled in this chapter aimed to analyze the project parameters on the safety risk of LEED credits. To achieve this objective, the scenario-based analysis was performed for three hypothetical scenarios. The selected factors were assigned to three cases, the first scenario was generated based on the minimum requirements of IHSA, the second scenario was generated with moderate site parameters and the third scenario depicted the project parameters at their best level. The three scenarios are depicted in Table 5-6. These three states are applied to the proposed BBN and the results are summarized in Table 5-7.

Table 5-6 Scenario Cases for Proposed BBN

Nodes	**Scenario 1**	**Scenario 2**	**Scenario 3**
Site Inspection	Performed	Moderate	Performed
Safety training	Provided	Moderate	Provided
Safety guidelines	Not Provided	Moderate	Provided
Experience or skill of workers	Unskilled worker	Moderate	Skilled worker
Sign warnings	Present	Moderate	Present
Safety equipment	Provided	Moderate	Provided
Poor Safety Management	False	Moderate	False
Slippery conditions	Present	Moderate	Absent
Exposure monitoring	Not Performed	Moderate	Performed
Maintenance of machinery	False	Moderate	True
Insufficient evacuation facilities	True	Moderate	False
Damaged equipment	Yes	Moderate	No

5.8 Result

Table 5-7 illustrates the overall safety hazards for the highest and lowest probabilities at different scenarios. The highest risk-causing and low risk-causing LEED credits for safety hazards are represented with their percentage probabilities.

Table 5-7 Scenario-based Hazard Probabilities for LEED Credits

Sr. No	**Scenarios**	**High-risk LEED credit**	**% overall hazard probability**	**Low-risk LEED credit**	**%overall hazard probability**
1	Scenario 1 (Minimum IHSA requirements)	Onsite renewable energy	69.4%	Wastewater treatment	11.1%
2	Scenario 2 (Moderate case)	Onsite renewable energy	70.5%	Wastewater treatment	22.4%
3	Scenario 3 (Best case)	Onsite renewable energy	46.3%	Indoor air quality	10.4%

BBN result can be implemented at pre-construction phase to identify main safety hazards. Project parameters differs from project to project. BBN will enable identifying the key risks as a result of project parameters. After identifying critical hazards, preventive measures can be implemented by safety managers.

5.9 Summary

This chapter analyzed how the probability of occurrence of safety hazards associated with LEED credits change with project parameters. BBN was used to perform this analysis. Netica software was used to perform BBN. A scenario-based analysis was performed to determine the probability of occurrence of safety hazards for each LEED credit. Recommendations were made based on the BBN result. The findings of this research will inform the construction industry on safety planning for construction projects.

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CHAPTER 6

BIM-BASED MITIGATION METHODS FOR LEED CONSTRUCTION HAZARDS

6.1 BIM in Construction Safety

Workers' health and safety have an indirect effect on the productivity of the project. BIM can identify dangerous workplaces through visualization and help prevent accidents (Cherkina et al., 2018). BIM has changed the way buildings are designed, executed, and managed. Safety assessment and hazard identification improved through a swift transformation of fundamental changes to the project, which is only possible using BIM (Chan et al., 2016). BIM provides efficacy, adaptability, and accessibility of the data. The information can then be made visible conveniently to identify safety hazards (Yi-Jao et al., 2018). BIM is changing the way safety can be approached by the AEC industry. Existing manual and paper-based safety processes were inefficient, hence, BIM was being implemented more and more in site safety management (Zhang et al., 2015).

This chapter presents BIM-based solutions to detect and mitigate health and safety hazards associated with LEED construction. This chapter evolves various strategies to minimize the fatality and injury rate related to each hazard, which is extracted from the conventional construction industry. Finally, a detailed application of BIM to minimize fall hazards is visualized in BIM.

6.2 Methodology

The methodology of this chapter is described in Figure 6.1. BIM-based solutions were assessed based on safety hazards caused in LEED building construction. Finally, a BIM mitigation method was proposed to prevent high-risk activity associated with LEED rating system, which was 'working on the roof for installing PV panels'.

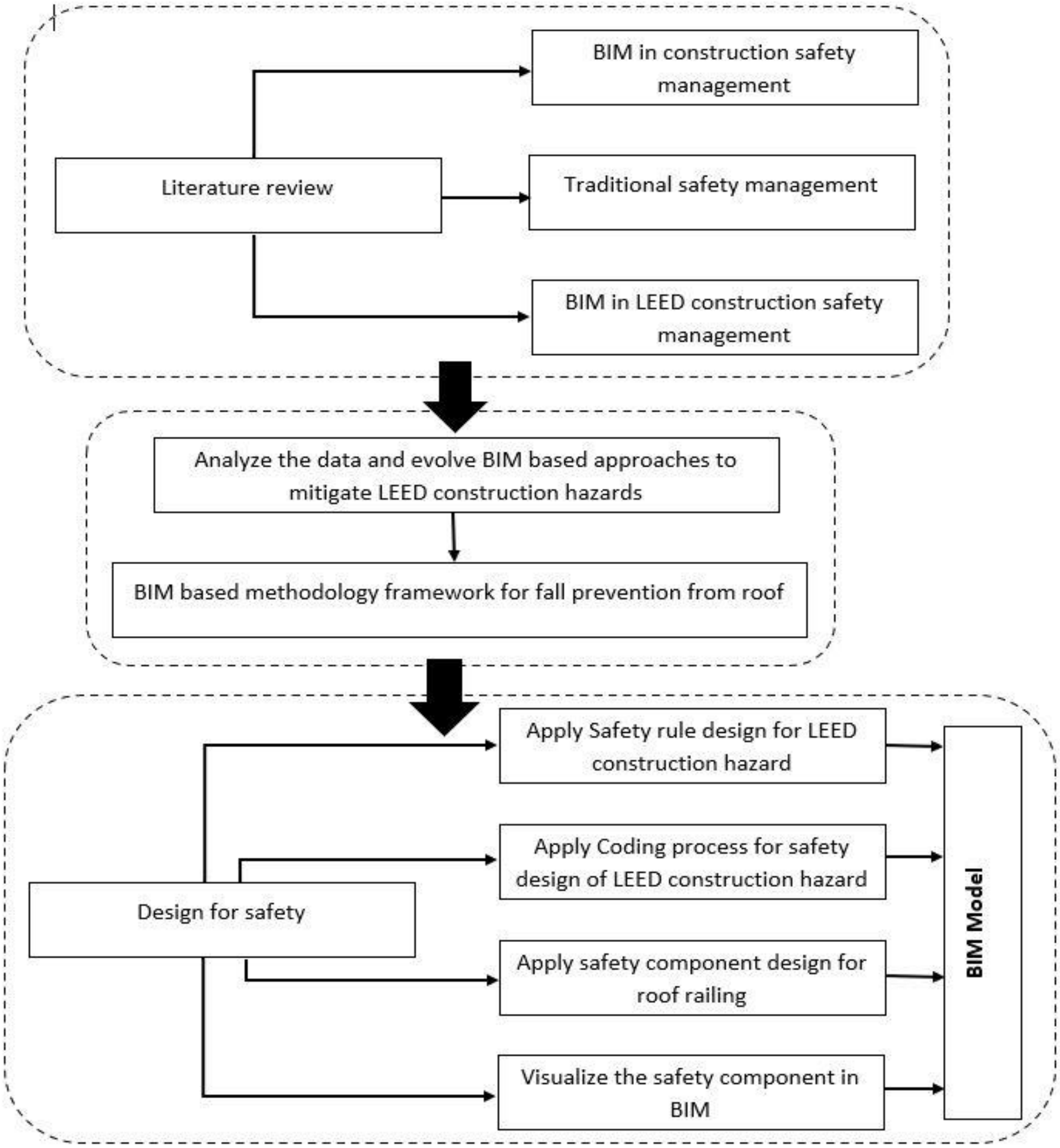

Figure 6-1 Methodology

6.3 LEED applicable BIM-based approaches

BIM was used for enhancing health and safety within a construction site through the following strategies.

6.3.1 Onsite conflicts/ clash: Numerous methods have been proposed for onsite conflicts, clashes, and similar hazards. Franco-Duran and Mejia (2016) proposed BIM-based spatial collision detection using a 4D BIM model to detect workplace conflicts. To decrease the percentage hazards, it was essential to identify probable safety hazards in the design phase and plan accordingly for risk mitigation. Hence, design using BIM-based safety planning, which was proposed by Kasirossafar et al. (2013), reduced the onsite conflicts. BIM and cloud-enabled real-time localization was a method for demonstrating the position of workers and equipment to prevent conflicts among them (Fang et al., 2016). A safety rule-based framework was integrated with BIM. Based on the safety rules, workers' safe and unsafe activities were tracked (Hongling et al., 2016).

6.4.2 Fall detection: BIM and cloud-enabled real-time localization approaches were used for fall detection. Clash, fall, and collapse usually took place during constant construction activities, where a single approach was used for multiple risks (Fang et al., 2016). The use of mobile tracking sensors was an effort to track workers' positions as well as the mobile equipment on-site to avoid multiple instances of accidents (Park et al., 2017). Clash detection (Tixier et al., 2017) and computer vision-based fall detection (W. Fang et al., 2018) were some other approaches to overcome fall or collapse hazards. Computer vision based fall detection is an automatic method that visualizes the locations that are susceptible to fall.

6.4.3 Fire safety: BIM was effectively demonstrated for fire safety and evacuation strategies using animation and serious gaming strategies. In serious gaming, the shortest paths and time to evacuate were analyzed at different intensities of fire (Zhang et al., 2015; Wang et al., 2014). Dynamic simulations by Norén, Nystedt, et al. (2018) to design fire safety using BIM were proposed. Fire protection drawings were incorporated in BIM to prevent fire hazards. Augmented reality systems by Yi-Jao et al. (2018) were integrated with BIM to give solutions to fire safety. This BIM approach was used to implement inspection of fire safety equipment using QR codes. A cloud inspection database was used for implementing this approach on the BIM platform.

6.4.4 Exposure to hazardous chemicals or materials: An automated decision support system (Kim et al., 2018) and site safety planning (Khoshnava et al., 2012) were the BIM-based techniques to prevent workers from coming in contact with hazardous substances. Safe and unsafe locations were predicted with the use of safety rules integrated into BIM.

6.4.5 Noise hazard: BIM-based noise hazard prediction (Cheng & Deng, 2015), noise plotting, and visualization using BIM (Cheng & Deng, 2015) contributed effective research areas to mitigate noise-related risks. There existed three stages, namely, noise data input, data processing, and data visualization. In each of these stages, noise data is collected, mapped, and then fused with BIM.

6.4.6 Indoor air quality assessment: An assessment of air quality was possible in BIM. This method compiled the quantification of emission rate and ventilation rate into BIM. A 3D model is prepared based on mass balance and pollutant concentration**.** The emission rate from a source was linked to the 3D model that calculates the emission rate. This method was applied in three steps: 1) emission rate quantification, 2) BIM integration, and 3) output from BIM. Based on the 3D model, concentration per hour was estimated (Altaf et al 2014).

Table 6-1 illustrates the high-risk LEED credits associated with a safety hazard. BIM approaches are suggested for each hazard based on literature.

Table 6-1 Summary of Applicable BIM Approaches in LEED Construction

LEED credit	**Safety hazard**	**BIM approaches**
• Brownfield redevelopment • Onsite renewable energy • Indoor air quality • Heat Island effect	**Fall**	• BIM and Cloud-enabled real-time localization • BIM Cloud and mobile tracking sensors • Clash detection using BIM • Computer vision-based approach • Safety rule-based framework and BIM integration
• Brownfield redevelopment • Onsite renewable energy • Construction waste management • Stormwater quality control	**Onsite conflicts**	• BIM-based spatial-temporal collision detection • Design using BIM-based safety planning • BIM and cloud-enabled real-time localization • Safety rule-based framework and BIM integration
• Brownfield redevelopment • Indoor air quality • Innovative wastewater technologies • Storage and collection of recyclables	**Exposure to hazardous materials**	• BIM-enabled automated decision support system • Site safety planning using BIM
• Brownfield redevelopment • Onsite renewable energy • Construction waste management	**Noise**	• BIM-based noise hazard prediction • Noise mapping and data visualization using BIM
• Onsite renewable energy • Construction waste management	**Fire breakouts**	• BIM-based serious game • Building evacuations using fire dynamic simulations and modeling • Fire protection in a BIM environment • BIM-based Augmented reality system

6.5 Safety solutions for high-risk LEED Credits

The analysis conducted in this research concluded ‘Onsite renewable energy’ conducts operations that need the worker to perform at heights. Working hours at the heights on the rooftops of the residential and commercial buildings have substantially increased the fatality rate. Operations required to install PV panels are dangerous. The credit involved activities associated with ladder and scaffoldings, which ultimately led to falling hazards.

6.6 BIM-based solution to mitigate fall hazard

The following BIM-based strategies can be used to minimize fall hazards.

6.6.1 Prevention through Design (PtD)

Prevention through Design (PtD) and planning for design were commonly used terms in the safety management field. Decisions made in the design phase had a substantial impact on the health and safety of workers during the construction and post-construction phases (Abueisheh et al., 2020). Planning for safety during the design phase can reduce fatalities by 50% during the construction process (Hongling et al., 2016). The designer's attitude and interpretation of workers’ health and safety played an important role in safety management (Poghosyan et al., 2018). The manual approach has been ineffective in terms of design for safety and has, therefore, introduced digital Dfs libraries. Many software programs were being developed to create libraries to design rule-based safety designs (Hossain et al., 2018).

If safety management was adopted in the early planning and designing phase of construction, preventive measures can be effectively implemented to minimize the fall hazard in LEED construction projects. The safety rule design classify construction safety information, define a safety rules, and the compile safety rule to computer readable format.This approach has been used for automatic identification of safety risks depending corresponding to the activity performed. A coding method was used to match the IDs of building component with a hazard information. BIM integration automatically identify the safety risk and the unsafe design factore associated with componenets. The safety rules used for the integration are coded ccorresponding to the type of hazard or accident and related parameters.

6.6.2 Rule-based safety design to prevent fall hazard

The following 4-step process could reduce the fall hazard in LEED building construction. This method identify unsafe design factors based on safety rules and BIM.

Step 1 – Categorizing safety information

Safety information is collected and then applied to classify the information as given in Table 6-2. The table presents the safety rule classifications and an example for each rule.

Table 6-2 Safety Rule Design

Rules for safety	**Example**
Accident type	Fall
Accident subject	Roof edges/ladder
Attribute	Vertical fall/slope
Parameter	Height off the roof/window sites
Safety rule	Safety guards
Prevention measure	Safety rails or harness /horizontal obstacles

Step 2 – Coding method for safety design

A coding method was used to assign unique identity codes to accident type, accident subject, parameter, etc. These codes were computer-readable and were designed according to the type of accident. Figure 6-2 represents an example of a coding process for safety rule design.

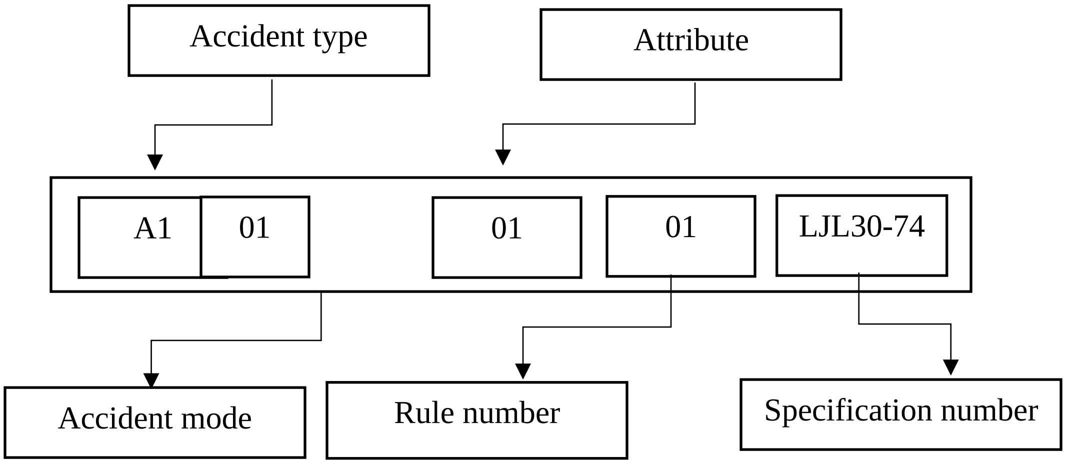

Figure 6-2 Coding process for safety design

The above-mentioned coding is used for safety rules. However, similar coding was done for the safety measures to be taken. For example, the safety component used for preventing falls from the roof is ‘railing’. Safety rules and safety components were interrelated. After completing the first step, which was identifying the safety rule, the required component was identified. Thus, the framework for coding for the component is as illustrated in Table 6-3.

Table 6-3 Component Design

Safety component	**Example**
Accident type	Fall
Accident subject	Roof edges
The slope of the roof	S = x
Prevention measure	Railings
Railing height	H = x

In this design, the preventive measure varies according to the safety rule. In the above example, the accident subject may vary from roof edges to roof slopes, whereas preventive measures can also vary from guard railings to horizontal planks for slip resistance. As the safety hazard and related activities vary, so did the suggested solution. This method was applied to identify and locate safety hazards and design safety components according to the requirements.

Step 3 - BIM and safety rule Integration

BIM stored and visualized the design information associated with each building component. BIM integrated a safety rule database, which is digital information of the designed component. Building information stored in BIM and the safety rule data were compared to identify the factors that are unsafe for design. Previously designed safety rule ID for fall hazard and component ID for a roof were compared to determine the accident subject matter. Once the safety rule ID and component ID were matched, the BIM system decided component parameters (for example the slope of the roof, the height of the roof). Thus, the solution was given for the identified hazard area according to the design information of the component.

Step 4 - BIM Visualization

BIM has limitations for analyzing and planning temporary structures. However, they can be visualized in BIM without utilizing rich information that can be extracted from BIM (Kim and Cho, 2015). Temporary structures can more efficiently be analyzed in 4D BIM. The 4D BIM model improved safety with the help of absolute safety plans (Pham et al., 2020).

A method was created in BIM to visualize the safety design for fall prevention from the roof. A BIM model was linked to the design safety rules. With the help of linked data the BIM model will extract the safety information related to the roof edges. The obtained information is as shown in Table 6-4. Table 6-4 presents the information extracted for the roof. Workers are susceptible to risks of falling while working on roofs. this information was used to automatically identify unsafe design factors to prevent the fall hazard.

Table 6-4 Extracted Information of Roof

Component ID	1010222
Elevation	3 M
Texture	By category
Size	Width or height or thickness
Position (coordinates)	X = 3500
	Y = 1200
	Z = 2100

The attributes are matched with the safety rules to give the final results for providing relevant safety component. In this method, IDs of the position of roof edge and its height are the attributes will be matched with a safety rule. Figure 6-3 illustrates a BIM model with the guard ralis to prevent safety hazard of fall from the roof. The guard rails are provided in the form of temporary structures.

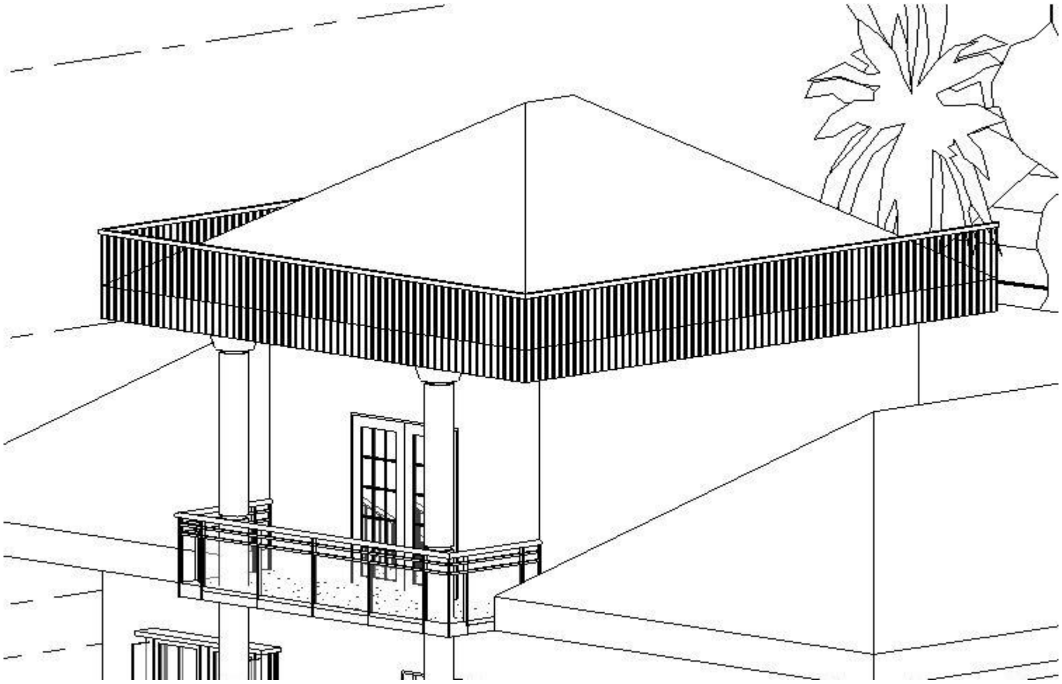

Figure 6-3 Automatic detection of guard rails for roof edges

6.6.3 Methods to add temporary structures in BIM

1) The compatible plug-in can be created BIM application that can be developed by following the BIM algorithm. Temporary structures like guardrails and scaffoldings can be automatically simulated in 4D BIM (Pham et al., 2020).

2) Automation of temporary structure planning can be incorporated on a BIM platform by developing a rule-based algorithm. The location of the temporary structure is possible based on the rules integrated with BIM (Cheng and Deng, 2015b).

3) 4D BIM can be programmed with some inbuilt families of temporary structures by the software programmers. This will eliminate the limitations of BIM related to the analysis of temporary structures for improving the safety of construction projects.

4) Compatible add-ins can be introduced for 3D software to visualize the safety components of the building structures.

5) The 'Massing and site' feature enables incorporating site components into a building structure. Similarly, this feature can be used to incorporate safety components into a building structure.

6.7 Summary

This chapter presents BIM-based solutions for safety management. 'Fall during PV panel installation' was identified as the high-risk activity in obtaining LEED credits. BIM-based solutions were proposed to mitigate fall risk. This chapter provides strategies for construction managers to protect worker health and safety by identifying the safety risks automatically and suggest preventive measures. This chapetrs provides implementation guidelines for execution, visualization and analysis of the temporary structures.

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CHAPTER 7

CONCLUSIONS AND FUTURE WORK

The main conclusions of this research are as follows:

FMEA revealed that activities associated with the implementation of LEED credits involved hazards to workers. When these activities were marked on a risk scale of 1 to 25, LEED credits with both high risk and low risk were determined. Onsite renewable energy was the high-risk LEED credit according to the FMEA risk analysis, while wastewater treatment had the lowest risk. The total risk of a LEED credit depended on the aggregated risk score of the individual modes of failure.

The risk analysis performed in this study showed that the onsite renewable energy credit in the LEED certification system poses a high risk. Working at varying heights for increased hours, handling different equipment, and working on slopes for installing PV panels has increased the fatality rate associated with this credit. Collisions or conflicts between moving vehicles, equipment, and workers were a major threat while pursuing LEED credits for brownfield redevelopment and construction waste management. Treating greywater caused a high level of exposure to hazardous material to human health.

A case study was performed to obtain optimal solutions from the combinations developed for the minimum cost and minimum safety hazard. The case study provided LEED point evaluation and incremental costs of the CEI building. The combinations were developed by applying a constraint. This constraint was the LEED points necessary to achieve gold certification. The Pareto frontier gave two optimal solutions, E and H, which are non-dominating solutions.

The proposed research work can inform the AEC industry about high-risk LEED credits. The results of FMEA will direct the construction industry to implement preventive measures for high-risk LEED credits.

Bayesian network analysis was used to determine the impact of project parameters on the hazard probabilities of LEED credits. The impact of the project parameters in three different scenarios was tested using the Bayesian belief network. Scenario 1 concluded that onsite renewable energy presented a high risk in the worst case. Wastewater treatment presented the lowest risk in worst and moderate scenarios. In scenario 3, when the project parameters were favorable, the impact remained the same on high-risk LEED credit but there was a drop in percentage hazard from 91% to 46%.

BIM-based solutions were proposed to mitigate the safety risks associated with LEED construction. A safety design approach was broadly explained and applied to a high-risk hazard. Safety rule design and component design were the primary steps of the framework. Furthermore, visualization of safety components using Revit software was performed.

7.1 Contributions

The following are key contributions of this research.

7.1.1 Risk Ranking of LEED credits: This research involved critical analysis of LEED credits to identify the risk level that can be computed using Failure Mode Effect Analysis. There is little evidence of LEED credit evaluation, and there is a lack of comprehensive study of the strategies and activities involved in LEED credit execution. FMEA demonstrated the severity of each credit to compare high-risk and low-risk LEED credits and ranked them in order.

7.1.3 Impact of project parameters on LEED buildings: The Bayesian network analysis demonstrated in this research assessed the impact of project parameters on the overall safety hazard of the LEED credit. This approach can be used by any analyst to check the impact of project parameters in different scenarios.

7.1.4 Introducing BIM-based solutions for LEED construction safety: This research incorporated BIM for mitigating the safety hazards in LEED construction. As the current literature does not focus on specific safety hazard mitigation strategies associated with LEED projects, this research encouraged the application of BIM in sustainable construction hazard mitigation strategies.

7.2 Limitations and Future Research Recommendations

The following are the limitations of this research and recommendations for extending the findings.

7.2.1 Lack of data for the critical examination of LEED credits: The available literature on high-risk activities was missing detailed implications of safety hazards related to LEED credits. Furthermore, there is no clear indication of the high-risk and low-risk LEED credits that can be prevented through strategic methods.

7.2.2 Limited data availability for safety hazards in green construction: Although substantial data was available for the conventional construction industry, green construction lacks reliable data for performing risk analysis. The available data sets were screened and processed thoroughly and can be used to perform risk analysis.

7.2.3 Data uncertainties: Uncertain data sets created obstacles in the process of individual LEED credit examination. Data uncertainties impacted the precision level of the findings. Smooth analysis of safety hazards related to green buildings was difficult due to this limitation.

7.3 Future Research

The following future research areas are proposed to extend the findings of this study.

- Data uncertainties can be minimized by experimenting with different methods of analysis that are capable of handling data uncertainties. Moreover, methods such as fuzzy logic can be used to account for data uncertainties. The findings and data in this research can be further analyzed to reduce the data complications of future research.
- The LEED rating system can be revised by future research to introduce safety parameters. Similar rating systems like

BREEAM and Green Globes can be analyzed to check their efficiency in terms of worker health and safety. Moreover, BIM can be introduced to tackle the safety hazards in green building rating systems.

- Safety management of LEED construction strategies is introduced in this research. Similar approaches can be examined for other LEED credits, and BIM can be extensively incorporated to execute preventive measures in LEED building construction if further studies in this field are motivated to do so.
- Calcuating the marginal costs of safety hazards is an important initiative that could extend the findings of this research. A marginal cost can be determined based on the costs for implementing preventive measures. The implementation cost of LEED credits and the marginal cost of the risks can be analysed to identify the best LEED credit combination.

APPENDICES

The data required for Bayesian networks analysis is extracted from various sources and in different forms. The following tables contain data in numerical and linguistic forms that are processed to enter percentage probabilities.

Appendix A

The following table contains data extracted from the U.S. Bureau of Labor statistics – fatal occupational injuries in 2018.

Struck by vehicle or object	46	Dust explosions	12
Caught in between objects		Exposure to harmful substances	71
Struck by a falling object	41	Exposure to extreme temperature	23
Fall from roof	56	Noise hazard	18
Fall from ladder	31	Exposure to oxygen deficiency	4
Fall from scaffolding	65	Struck during excavation, trenching, and cave-in	12
Fall due to slips and trips	32	Caught in running equipment	11
Fire explosions	20		

Appendix B

Table B1 to B5 illustrate the conditional probability tables from Netica. They are scaled to low, medium, and high probabilities. These probabilities are used to calculate the overall risk of the LEED credit.

B1 Conditional probability table for fall hazard

Fall from ladder	**Fall from roof**	**Fall from excavated edges**	**Fall from scaffolding**	**Fall hazard**
Yes	Yes	Yes	Yes	High
Yes	Yes	Yes	No	High
Yes	Yes	No	Yes	High
Yes	Yes	No	No	High
Yes	No	Yes	Yes	High
Yes	No	Yes	No	Medium
Yes	No	No	Yes	Medium
Yes	No	No	No	Medium
No	Yes	Yes	Yes	High
No	Yes	Yes	No	Medium
No	Yes	No	Yes	High
No	Yes	No	No	Medium
No	No	Yes	Yes	Low
No	No	Yes	No	Low
No	No	No	Yes	Low
No	No	No	No	Low

B2 Conditional probability table for hazard due to collision/conflicts

Struck by a falling object	Struck by object - equipment	Caught in-between object	Stuck by falling from moving object	Collision/ conflict hazard
Yes	Yes	Yes	Yes	High
Yes	Yes	Yes	No	High
Yes	Yes	No	Yes	Medium
Yes	Yes	No	No	Medium
Yes	No	Yes	Yes	Medium
Yes	No	Yes	No	Medium
Yes	No	No	Yes	Medium
Yes	No	No	No	Low
No	Yes	Yes	Yes	Medium
No	Yes	Yes	No	High
No	Yes	No	Yes	Low
No	Yes	No	No	Low
No	No	Yes	Yes	Low
No	No	Yes	No	Low
No	No	No	Yes	Low
No	No	No	No	Low

B3 Conditional probability table for hazardous exposure

Dust and suffocation	Temperature	Toxic materials exposed	Heavy materials exposed	Hazardous exposure
Yes	Yes	Yes	Yes	High
Yes	Yes	Yes	No	High
Yes	Yes	No	Yes	High
Yes	Yes	No	No	Medium
Yes	No	Yes	Yes	High
Yes	No	Yes	No	Medium
Yes	No	No	Yes	High
Yes	No	No	No	Low
No	Yes	Yes	Yes	High
No	Yes	Yes	No	Medium
No	Yes	No	Yes	Medium
No	Yes	No	No	Low
No	No	Yes	Yes	Low
No	No	Yes	No	Low
No	No	No	Yes	Medium
No	No	No	No	Low

B4 Conditional probability table for noise hazard

High noise machinery	Heavy material transportation	Noise hazard
Yes	Present	High
Yes	Absent	Medium
No	Present	Low
No	Absent	Low

B5 Conditional probability table for fire hazard

Fire due to electrical glitch	Fire explosions due to dust	Fire hazard
True	True	High
True	False	Medium
False	True	Low
False	False	Low

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