OCCUPATIONAL HAZARD ASSESSMENT IN CONSTRUCTION PROJECTS: A CASE STUDY

By

Miss Yuke JIANG

A Thesis Submitted in Partial Fulfillment of the Requirements
for Master of Engineering ENGINEERING MANAGEMENT
Department of INDUSTRIAL ENGINEERING AND MANAGEMENT
Silpakorn University
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MissYuke Jiang

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The initial and most crucial phase in the safety management process is assessing occupational hazards. It is an indispensable component of intricate work systems, particularly construction ones. The application of multi-criteria decision-making tools is demonstrated in this research as an example. The analytic network process, the analytic hierarchy process, and fuzzy failure mode and effects analysis are some of the tools packed systematically. The case simulation is a construction site constructing a residential building in Kunming. The construction site's occupational health and safety supervisor pointed out ten construction functions, eleven hazard factors, and eight causes. The safety team conducted a brainstorming meeting to conduct the pairwise comparisons. Then, six steps of the proposed occupational hazard assessment technique are conducted. It is demonstrated via the case study that decision-making produces outcomes that are distinct from those obtained through conventional failure mode and effects analysis. It can address the shortcomings of the traditional tool, including the dependency of components, the relative importance of missed factors, and the difficulty of calculating values. Additionally, this essay demonstrates that the construction functions, danger factors, and causes are assessed reasonably.

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CHAPTER 1
INTRODUCTION

1.1 Motivation

The construction industry has experienced significant growth relative to the global population in recent years. Therefore, there is a requirement for additional shelters, workspaces, infrastructures, and amenities, which leads to the expansion of the construction business as a significant sector in every economy (Al-Anbari et al., 2015; Osei-Asibey et al., 2021). In 2016, the construction industry contributed over 11% to the global Gross Domestic Product (GDP). By 2020, this sector is projected to make up 13.2% of the world's GDP (Choi et al., 2019). Nevertheless, despite the recent advancements in construction safety, the risk of accidents remains much higher than in most other industries (Orji et al., 2016). The high incidence of injuries in construction work can be linked to the specific characteristics of this field, which require the use of heavy machinery and working under challenging conditions.

Construction projects inevitably involve inherent risks characterized by high degrees of unpredictability. Therefore, it is prudent to prioritize safety and risk management in building projects (Hoła and Szóstak, 2014; Peñaloza et al., 2020). Considerable endeavors have been dedicated to developing safety systems to avert accidents and enhance safety performance.

The most efficient method for enhancing safety performance is to prevent accidents and minimize uncertainty prior to their occurrence. Therefore, evaluating safety-related hazards is the basis for establishing safety management. Consequently, risk assessment is regarded as a crucial element of safety management systems (Pheng & Shiua, 2000; Cheng et al., 2004; Provan et al., 2020).

Various approaches have been employed to evaluate the hazards related to workplace safety. Among them, Failure Mode and Effects Analysis (FMEA) is well recognized as a prevalent method (Falcone et al., 2013). In this context, fuzzy logic can be integrated with the FMEA method to address the limitations of the conventional FMEA approach. The Fuzzy FMEA approach not only overcomes these limitations but also yields superior outcomes when dealing with ambiguous concepts and imprecise data (Pinto et al., 2011). This practical advantage instills confidence in its effectiveness.

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In addition, the conventional FMEA method is not sufficiently flexible in incorporating expert opinions. Therefore, a Fuzzy Expert System (FES) can be implemented to obtain the necessary flexibility (Alizadeh et al., 2022).

The uncertainty surrounding occupational accidents can be attributed to two factors: random variations caused by environmental, natural, or temporal changes (statistical uncertainty) and uncertainty arising from relative information (such as expert opinions) or the dispersion of data (non-statistical uncertainty) (Raheem and Issa, 2016). However, due to the limited availability of prior information for analysis and the absence of feedback from the workshop in the early stages of the project, it is necessary to consider the subjective probability condition (Forteza et al., 2016).

This study aims to implement the Fuzzy Probabilistic Expert System (FPES) of Amiri et al. (2017) on a sample construction project in Kunming. This advanced method quantifies occupational safety hazards and provides their rankings. Additionally, the statistical uncertainty inherent in the risk management concept is included.

1.2 Research Objectives

This study aims to implement occupational hazard assessment based on multi-criteria decision-making. It uses decision techniques such as failure mode and effects analysis, the analytic network process, the analytic hierarchy process, and fuzzy rule-based techniques. The practical framework is depicted systematically.

1.3 Research Contributions

1. A sample case for FPES in occupational hazard assessment in construction industry.

2. It is a practical case with advanced mathematics, but rational, which benefits other construction projects.

3. To investigate the advantages and disadvantages of using FPES in the construction industry.

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1.4 Scopes and Limitations

1. This study is a combination of survey research and quantitative research; however, the primary one is the quantitative research that attempts to propose a practical tool and the case is about collecting data from the case study.

2. The survey research has a specific manner. Thus, the result from the case study cannot guarantee other cases in general.

3. The data is collected between April 2024 to May 2024

1.5 Acronyms

AEB	Accident Evolution and Barrier Function
AHP	Analytical Hierarchical Process
CREAM	Cognitive Reliability and Error Analysis Method
EA	Energy Analysis
FMEA	Failure Mode and Effective Analysis
FMECA	Failure Mode Effect and Criticality Analysis
FPES	Fuzzy Probability Expert System
FTA	Fault Tree Analysis
HAZOP	Hazard and Operability Studies
ISRS	International Safety Rating System
MORT	Management Oversight and Risk Tree
ORA	Occupational Risk Assessment
PHA	Preliminary Hazard Analysis
SCHAZOP	Safety Culture Hazard and Operability Study
SHE	Safety Health and Environment Audit
SMS	Safety Management System
TEP	Timed Events Plotting
THERP	Technique for Human Error Rate Prediction

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CHAPTER 2
LITERATURE REVIEW

This chapter examined relevant background theories in the literature. We started with a review of the construction industry in section 2.1. Then, section 2.2 breifely assessed the concepts of safety engineering and management. We deep down review, section 2.3, on occupational hazard assessment in construction industry. The failure mode and effective analysis is evaluated in section 2.4. Section 2.5 illustrated the concept, method, and analysis of the fuzzy probabilistic expert system which is the primary tool in this study.

2.1 Construction Industry

Ancient construction relied on natural resources, climate, and local skills to create a shelter that considered the specific climatic conditions and the properties of available construction materials (Ngowi et al., 2005). The oldest shelters and villages were constructed using stone, clay, and other materials from nearby forests. These constructions provided shelter from various weather conditions, such as low temperatures, gusty winds, rainfall, and other types of precipitation. The construction of these shelters using the listed materials involved several trials, errors, and the accumulated wisdom of generations of builders who continued to utilize effective procedures and discarded ineffective ones. In the initial phases of community development, construction was a collective endeavor that included the participation of every community member. Individuals actively participated in all phases, from initial planning to actual production, thereby incorporating their personal values and identities into the end product, resulting in a faithful representation of their respective cultures.

Conquests were a common phenomenon in early societies. Amidst these disputes, factions would engage in combat, and the individuals from the losing society would be captured as captives by the triumphant community. Frequently, the victors assumed authority over the economic activities of the villages they had obliterated. Using this authority, they employed the resulting finances, along with their own, to replace the defeated community's infrastructure with their own design. This pattern is evident across the entire span of European history. For example, the early Greek settlements around the Mediterranean utilized mud as the primary building material for their houses, which were then reinforced with timber frames. Marble was used to build temples and theaters in subsequent periods. The Romans, who founded the Roman Empire, not only captured these towns but also influenced their methods of construction and the whole culture of the people. The Roman Empire, with its center in Rome, encompassed a territory extending from Great Britain to the Middle East. During its peak, from the 2nd to the 1st centuries BC, the population of the Roman Empire ranged from 60 to 100 million individuals. The Romans possessed a remarkable infrastructure, with most edifices-built stone and marble.

Marcus Vitruvius Pollo authored the inaugural comprehensive treatise on building and construction during the era of the Roman Empire. He covered subjects such as construction materials, architectural style, design of different types of buildings, construction methods, architectural physics, astronomy, and building machinery. This book was unprecedented in the annals of human history. Vitruvius documented the hypocaust, a heating system used in public baths and the residences of influential and affluent individuals, along with other details. The hypocaust, invented in the 1st century BC, consisted of a raised floor supported by columns and heated by hot gasses generated from a furnace at one end and evacuated by a chimney at the other. Following the collapse of the Roman Empire in 476, characterized by the decline of Rome, the progress of construction and architecture ceased for a prolonged period. The Romans played a significant role in introducing a splendid new era in building and construction. During this period, participation in different building areas was the primary method by which construction skill was passed down from generation to generation (Kim, 2010).

The period that occurred after the decline of the Roman Empire is commonly known as the “Middle Ages,” and it encompasses the years from 476 to 1492. Although fewer construction operations were occurring, the area still witnessed the creation of magnificent churches and other architectural wonders, such as those in Pisa. During this era, there was a noticeable rise in the level of organization observed in the construction sector, particularly in deforestation, stone extraction, brick and tile production, and lime burning for the construction of cathedrals and other structures. The training and education of artisans during the Middle Ages led to an elevation in their social standing, a notable advancement facilitated by the stability of the age. This development directly impacted the construction activities carried out during that period. The emergence of guilds in the construction industry, as seen in other sectors, facilitated a more systematic and structured approach to building construction, which in turn contributed to the significant growth of this industry (Spufford, 1988). Craft guilds were professional associations in Europe that aimed to safeguard and oversee craftspeople engaged in a particular trade. These entities were commonly referred to as “guilds.” Their traits were broadly consistent throughout Europe. The guilds were organized hierarchically, with individuals often belonging to one of three specific categories: masters, journeymen, or apprentices. The master mason was fully committed to finishing the construction of the building he was working on. In addition to designing and overseeing the construction, he frequently resided on the premises, thus making significant contributions (Linder, 1994).

The Renaissance, which followed the Middle Ages, was marked by a resurgence in building, construction, and science. In 1570, the Italian architect Andrea Palladio published a comprehensive and ambitious series of four volumes on architecture, marking a significant milestone in the field (Goldberg & Griffey, 2019). It originated a novel Palladian aesthetic. Nevertheless, in this particular era, innovative construction methods replaced the previous exclusive control maintained by the medieval construction guilds. The proliferation of innovative construction methods led to this outcome. Decrees and acts were used to prohibit craft groups, ultimately resulting in the decline of guilds and the emergence of professional designers and contractors. Overall, this period is notable because of the shift of the construction sector from a fragmented and chaotic state to a more ordered and systematic one.

2.2 Safety Engineering and Management

2.2.1 Safety engineering definition

Safety engineering is the systematic design and implementation of measures to mitigate the risk of accidents in workplaces. Engineering Safety Concepts offers comprehensive methodologies and strategies to minimize accidents by employing a risk management procedure to identify and eliminate dangers through design. Incidents are capable of occurring and indeed do occur. Workplaces and industries that utilize equipment, chemicals, and other potentially dangerous elements are prone to incidents that can result in injuries or even fatalities if a thorough engineering safety approach is not implemented. Due to its multidisciplinary nature, safety engineering attracts many professionals who actively contribute to accident prevention and safety engineering.

2.2.2 Safety engineering design

Safety engineering ideas serve as the framework for safety and industrial design engineers to create equipment, systems, processes, and facilities that are inherently safe. If safety engineers are hired at the beginning of a design process, they can offer valuable information on how humans will interact with the equipment and facility design. Early implementation of safety design should aim to assure both the physical safety of individuals and the development of an operational concept that can effectively handle both industrial and non-industrial incidents while also minimizing their impact. Engineered safety includes the implementation of fail-safe process equipment, fault-tolerant equipment, fire safety measures, and enclosed hazardous systems to prevent any potential harm to workers and the environment.

Safety engineering plays a crucial role in removing hazards that would otherwise be managed through administrative controls or the use of personal protection equipment as a barrier between a hazard and a worker. The implemented safety measures consist of machine guards, utilization of less dangerous equipment, establishment of maintenance schedules to ensure equipment safety, implementation of audit and inspection procedures, selection of safer tools, conducting safety reviews for new equipment, providing employee maintenance training, designing a safe flow of material and people within the facility, and conducting risk analysis for both potential human-caused and natural incidents.

The principles of safety engineering design are all-encompassing, taking into account every environmental factor within the workplace. This includes lighting, noise levels, atmospheric pollutants, ambient and localized temperature variations, slip resistance of flooring materials, emergency escape routes, and fire suppression and alarm systems. By considering all these factors, safety engineering ensures a comprehensive approach to workplace safety.

The safety assessment of incoming utilities is a critical aspect of safety engineering. It involves verifying the availability of reliable backup resources for electricity and water systems, which are essential for the operation of key processes. Additionally, the evaluation of electrical systems is aimed at preventing the introduction of extra facility expansion or equipment that could place excessive strain on the electrical distribution system. This proactive approach to utility management is a key part of safety engineering.

2.2.3 Safety management definition

Safety management uses a set of principles, frameworks, processes, and actions to prevent accidents, injuries, and other adverse outcomes that may result from using a service or product. This role supports managers in effectively fulfilling their responsibilities for designing and implementing operational systems. It is achieved by either predicting system weaknesses before errors occur or identifying and rectifying them through professional analysis of safety incidents.

Safety management is a methodical approach to overseeing safety, which includes establishing the appropriate organizational framework, responsibilities, rules, and procedures. Safety management is a crucial job inside an organization that focuses on identifying, evaluating, and effectively reducing all potential safety risks. By doing so, it significantly contributes to the overall safety of the organization, making the audience feel the impact of their work.

2.2.4 Safety management system

A Safety Management System (SMS) is a set of organized processes implemented throughout an organization to facilitate informed decision-making based on risk assessment in daily business operations. Safety Management Systems enable enterprises to provide products or services with the utmost level of safety and ensure the maintenance of safe operations. SMS can also fulfill official obligations, such as those outlined in Title 14 of the U.S. Code of Federal Regulations (CFR), which are enforced by the Federal Aviation Administration (FAA). The International Civil Aviation Organization (ICAO) states that the fundamental components of a safety management system are hazard identification, occurrence reporting, risk management, performance measurement, and quality assurance.

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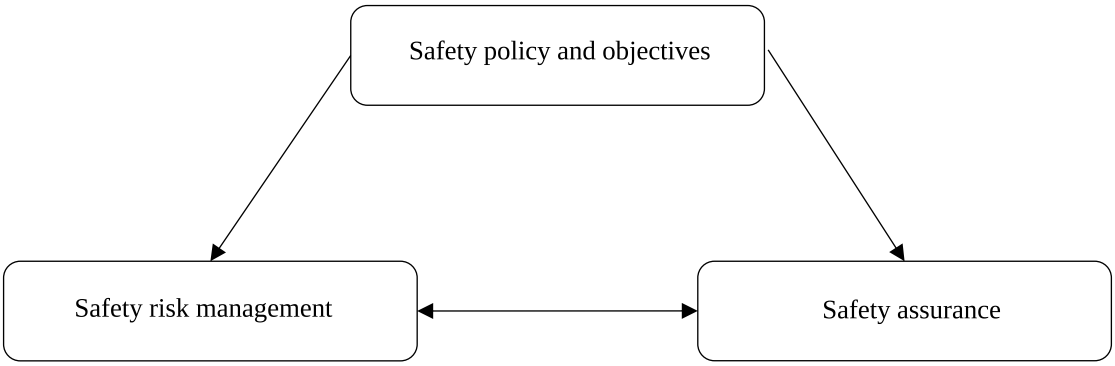


Figure 2.1 Safety management system.
Source: Manawis (2024)

A safety management system primarily offers a methodical way to oversee and mitigate safety hazards in operational activities. Additionally, it seeks to enhance safety by leveraging current procedures, showcasing corporate responsibility, and strengthening the overarching safety culture. Efficient safety management is essential for operating and expanding the business, particularly in high-risk sectors such as aviation, energy, maritime, and construction, where health and safety are of utmost importance. Although first intimidating, the development of safety management systems is crucial for the promotion and maintenance of workplace safety. By using an appropriate technical solution, such as a digital platform, we may optimize and simplify this procedure.

There are several advantages to having a safety management system, including:

1) Enhanced safety risk management procedures: Utilizing a digital platform with complimentary checklist templates and an intelligent form creator, we may effortlessly discover perilous working situations, evaluate safety hazards, and impose control measures.

2) Enhanced communication efficiency: Promote a culture of collaboration and enhance teamwork by encouraging openness among workers and enabling seamless dissemination of all crucial information.

3) Consolidated documentation: Utilizing a digital platform that enables cloud storage, we can effortlessly distribute files among colleagues at any time and location. Having a single, consolidated repository also enables us to easily access any audit trail we generate, which promotes ongoing enhancement.

2.2.5 Components and elements of SMS

The structure of safety management systems consists of four components. The following items are:

1) Policy and Objectives for Ensuring Safety
2) Safety Risk Management
3) Ensuring Safety
4) Promotion of Safety

Every SMS component has features that delineate precise requirements for the effective development and upkeep of a safety management system. The 12 safety management system elements, which were originally developed by ICAO and have since been adopted by various industries, are:

1) Dedication of management
2) Safety accountability and responsibilities
3) Selection of essential safety personnel
4) Facilitation of emergency response planning coordination
5) SMS documentation
6) Identification of hazards
7) Assessment and mitigation of safety risks
8) Monitoring and measuring safety performance
9) Change management
10) Ongoing enhancement of the SMS
11) Instruction and learning
12) Communication around safety

The constituents and constituents of a safety management system can be most comprehensively comprehended together as depicted in Table 2.1.

Table 2.1 Framework of SMS.

Components	Elements
1. Policy and Objectives for Ensuring Safety	• Dedication of management • Safety accountability and responsibilities • Selection of essential safety personnel • Facilitation of emergency response planning coordination • SMS documentation
2. Safety Risk Management	• Identification of hazards • Assessment and mitigation of safety risks
3. Ensuring Safety	• Monitoring and measuring safety performance • Change management
4. Promotion of Safety	• Ongoing enhancement of the SMS • Instruction and learning

Source: Manawis (2024)

2.3 Occupational Hazard Assessment in Construction Industry

The ever-changing nature of the construction sector necessitates the implementation of more effective approaches to project management in construction. The majority of construction organizations currently face challenges related to uncertainty, complexity, low performance, and inefficiency in their building projects. Hence, it is crucial to identify effective remedies for regions that want enhancement.

Additionally, it is essential to implement techniques that demonstrate a novel approach to enhancing performance and encouraging best practices on building sites (Demirkesen & Zhang, 2021).

The construction sector is inherently perilous, with a high incidence of both fatal and non-fatal occupational injuries, mostly due to its distinctive characteristics. The situation is marked by constant fluctuations, utilization of diverse resources, unfavorable working conditions, lack of stable employment, and challenging settings (such as noise, vibration, dust, cargo handling, and direct exposure to weather). Moreover, it necessitates the synchronization of various interrelated contractors, sub-contractors, and operations, which might lead to heightened susceptibility to accidents.

Occupational injuries and illnesses have a significant influence on both safety and health, as well as the economy, due to the substantial expenditures associated with work-related injuries. The issue of construction safety has been prominent due to the rising premiums for workers' compensation insurance, which may be attributed to a significant increase in the costs of medical treatment and recovery for work-related injuries. Research conducted across several sectors indicates that the construction business exhibits an above-average incidence of injuries and associated expenses.

An ORA process involves collecting information that enhances understanding of a specific hazardous scenario. This information is typically characterized by uncertainties, ranging from ambiguous or indistinct characteristics (such as inaccurate borders) to an excessive amount of data or even contradictory information (resulting from several sources). Therefore, ambiguous data hinders a comprehensive understanding of the facts and does not aid in the process of making informed decisions. Probabilities play a crucial role in traditional ORA methodologies. However, there is often a lack of clarity and understanding regarding their interpretation and use, which can undermine the effectiveness of the study.

2.3.1 Source of accidents

Several significant factors affect safety performance in the construction sector, including:

1) Inadequate work and safety organization - safety measures should not only be implemented on-site. To ensure safety, it is necessary to carefully design and establish specific procedures that can be efficiently executed in the field. Consequently,

it is essential to have a Safety, Health, and Ergonomics (SH&E) expert present during the procurement and preconstruction stages of a project.

2) Company size - the majority of construction companies are small businesses, which makes it challenging to guarantee internal expertise in safety matters. Additionally, these companies often have limited financial resources for implementing health and safety measures.

3) Absence of coordination - the building sector comprises numerous specialist groups collaborating within the same area. Construction projects commonly entail the participation of numerous employers and a wide range of trades, such as roofers, carpenters, electricians, plumbers, painters, and others. These trades perform a diverse array of duties at project sites.

4) Economic and temporal constraints can lead to the relaxation of rules and processes, resulting in actions that are characterized by recklessness.

5) Insufficient standardization of data, leading to a dearth of information regarding dangers, accidents, and similar occurrences.

6) Inadequate internal and external communication - for instance, in numerous nations, a significant section of the workforce lacks proficiency in the local language, making it challenging for safety managers to effectively convey potential hazards.

7) Inadequate worker engagement in safety problems - workers should actively participate in the creation of safety programs and contribute to finding solutions.

8) The dynamic nature of a construction site significantly impacts safety and health. Unlike other industrial settings, where operations are typically repetitive and confined to specific apparatus locations, building sites necessitate and facilitate frequent mobility of personnel between different areas.

9) Worker specialization - frequently, workers receive training in a singular, highly specialized construction application, resulting in limited familiarity with various materials and equipment present in the job.

10) Workers in this industry bear a greater responsibility for their own safety and the organization of their workplace as the site environment undergoes daily changes.

11) Insufficient training and weariness of practitioners, especially in the case of heavy machinery operators, can have a significant impact on pedestrians and nearby individuals, such as crane operators.

12) Inefficient equipment selection, utilization, or inspection - choosing the right equipment, using it correctly, and regularly inspecting it are crucial for maintaining high efficiency, productivity, and safety standards on the construction site.

13) Insufficient safety consciousness among senior executives and project leaders. The absence of oversight and regular gatherings - stemming from a deficiency in managerial dedication to safety affairs.

14) Inadequate preventative and protection equipment - caused by limited funding for implementing health and safety measures and a lack of safety culture.

15) Construction professions sometimes require workers to travel significant distances, which can result in the displacement of families and an increased likelihood of engaging in risky behaviors such as alcohol and drug use.

16) Construction workers are exposed to enduring health hazards as a result of the strain caused by intermittent employment and the anxiety stemming from the uncertainty of receiving regular paychecks, which is often due to unstable contracts and the lack of commitment from certain companies.

2.3.2 Accident costs

Throughout history, the construction industry has consistently posed significant risks for both fatal and non-fatal injuries, making it one of the most hazardous vocations globally. The 2007 injury and illness data published by the LABORSTA – ILO (a labor statistics database) reveals that the construction industry in the USA has a fatality and disabling injury rate about three times higher than the average for all industries. According to the Portuguese Statistics National Institute, about 50% of fatal incidents in Portugal between 2000 and 2006 took place in the construction business. These statistics, while alarming, also underscore the preventable nature of many construction accidents. Construction accidents undoubtedly have significant financial effects, but with the right safety measures and precautions, many of these incidents can be avoided.

The costs associated with injuries might vary significantly, depending on the occupation and the specific body component that is affected. Leigh and Miller (1997) found that construction laborers and carpenters are two occupations that incur significant expenses due to work-related injuries and illnesses. In their study, Dement and Lipscomb (1999) discovered that roofers and carpenters had medical expenses that were greater than the average. This conclusion was drawn after analyzing over 30,000 workers' compensation claims from members of the North Carolina Homebuilders Association between 1986 and 1994. These findings highlight the substantial financial burden that construction injuries place on both individuals and the industry as a whole, underscoring the need for cost-effective solutions.

In a study conducted by Waehrer et al. (2007), it was discovered that construction laborers had the highest number of fatalities, with a total of 299. This led to the highest average annual mortality costs, amounting to $1200 million. Lipscomb et al. (2006) analyzed over 20,000 workers' compensation claims made by construction workers in Oregon from 1990 to 1997. They found that falls were the most expensive type of injury for residential carpenters, with 14% of claims accounting for 83% of the costs. These claims also made up 25% of workers' compensation payments, totaling over $10 million. According to Shah et al. (2003), the direct expenses associated with accidents and illnesses caused by wood framing in residential construction amounted to more than $197 million in Washington State. This estimation was derived from workers' compensation claims data collected between 1993 and 1997. According to Ringdahl (2001), who references a study conducted by Bearson and Coleman in 1997, the economic costs of occupational injury and sickness in nine European nations were estimated. The study found that the majority of these expenses ranged from 2.5% to 6% of the Gross Domestic Product (GDP) of each country.

2.4 Failure Mode and Effective Analysis

2.4.1 FMEA fundamentals

Failure Mode and Effects Analysis (FMEA) is a systematic approach to identify and analyze all potential failure modes within a system. It involves investigating the root causes of these failure modes, assessing their impact, and developing plans to address the identified problems (Mohammadi & Tabakolan, 2013).

Risk Priority Numbers (RPNs) are utilized in conventional Failure Mode and Effects Analysis (FMEA) to determine the risk priority of discovered failure modes. The range of the Risk Priority Number (RPN) spans from 1 to 1,000 and can be determined by multiplying the scores of risk variables, including incidence (O), severity (S), and detection (D).

$$RPN = O \times S \times D \tag{2.4}$$

where O is the failure probability, S is the failure severity, and D is the power of detection.

Multiple studies have endorsed the utilization of the Failure Mode and Effects Analysis (FMEA) technique for risk management purposes. Carbone and Tippett (2004) introduced the utilization of Failure Mode and Effects Analysis (FMEA) within the broader context of project risk management. The PRN number was utilized as a computational instrument to ascertain the utmost perilous hazards. Sharma et al. (2005) utilized a case study from the paper sector as an instance example to showcase the implementation of FMEA (Failure Mode and Effects Analysis) and fuzzy logic in the evaluation of risks. The ratings for the risk factors were assessed by utilizing linguistic variables, which were subsequently expressed as fuzzy numbers. Their research showed that using fuzzy linguistic modeling was an excellent way to address the uncertainty that is present in traditional evaluation methods. However, the typical Failure Mode and Effects Analysis (FMEA) does have certain limitations. Quantifying the likelihood of failure events in FMEA might be arduous or potentially unattainable in certain instances (Yang & Wang, 2015). Simultaneously, a substantial portion of the information in the Failure Mode and Effects Analysis (FMEA) is communicated through the utilization of terms like ‘likely’ and ‘Very high.’ Various combinations of O, S, and D can yield identical results in RPN analysis, although the associated risk implications can vary significantly between various scenarios. Take, for instance, two separate instances, one with the values O = 3, S = 5, D = 3, and the other with the values O = 9, S = 5, and D = 1, respectively. While the combined RPN value of both occurrences will equal sixty, the risk implications of both events may differ. Liu et al.

(2012) conducted extensive research and created a comprehensive compilation of all the problems found in FMEA. They highlight the omission of considering the relative importance of O, S, and D and instead assume that all three components hold equal value.

2.4.2 Original FMEA

Detection refers to the ability to identify a potential risk event with sufficient time to make necessary preparations and take appropriate action to mitigate the risk. The values of these three elements can vary from “1” to “10.” Components of the system with a high-Risk Priority Number (RPN) are considered to be more critical than those with lower values (Gavrysh & Melnykova, 2019). Research has shown that the traditional Failure Mode and Effects Analysis (FMEA) is a highly effective approach for reducing the likelihood of errors and failures inside a system. Conversely, the conventional Reverse Polish Notation (RPN) method has faced significant criticism in scholarly publications due to many factors (Yang & Wang, 2015). In the classic FMEA, the severity, occurrence, and detection are measured on a scale, as presented in Tables 2.2 to 2.4.

Table 2.2 Quantification of severity.

Effect	Criteria: severity of effect	Rank
Hazardous	Failure is a perilous occurrence that might happen unexpectedly. It hinders the proper functioning of the system and/or leads to breaches of government-imposed laws and regulations.	10
Serious	Failure can be characterized as the presence of hazardous outcomes or the breach of governmental regulations or criteria.	9
Extreme	The product is inoperable and has become devoid of its fundamental functionality. The system is entirely ineffectual.	8

Table 2.2 Quantification of severity. (continued)

Effect	Criteria: severity of effect	Rank
Major	The product's performance is significantly impaired, although its continued regular functioning. There is a potential for the system to be non-functional.	7
Significant	The performance of the product is declining. The functions of comfort or convenience may not be effective.	6
Moderate	The impact on product performance is rather minimal. Product repair is essential.	5
Low	Negligible influence on the overall efficacy of the product. The object does not require any form of repair.	4
Miner	A negligible influence on the overall functionality of the product or system.	3
Very Miner	Negligible influence on the overall efficiency of the product or system.	2
None	There is no impact or influence.	1

Table 2.3 Scaling of events.

Probability of failure	Possible failure rates	Rank
Extremely high	≥ in 2	10
Very high	1 in 3	9
Repeated failures	1 in 8	8
High	1 in 20	7
Moderately high	1 in 80	6
Moderate	1 in 400	5
Relatively low	1 in 2,000	4
Low	1 in 15,000	3
Remote	1 in 150,000	2
Nearly impossible	1 in 1,500,000	1

Table 2.4 Scalability of detection.

Detection	Criteria: likehood of detection by design control	Rank
Absolute uncertainty	Either the design control fails to recognize a potential failure mode or the cause of failure that follows, or there is a complete absence of design control.	10
Very remote	There is a minimal likelihood that the design control will be able to identify a potential failure mode or a future cause of failure.	9
Remote	There is a slight chance that the design control may detect a potential failure mode or a future cause of failure.	8
Very low	There is a low probability that the design control will be able to identify a likely cause of failure or a subsequent mode of failure.	7
Low	The likelihood of the design control identifying a probable failure mode or future failure cause is minimal.	6
Moderate	It is quite probable that the design control will be able to identify a potential failure mode or a future failure cause.	5
Moderately high	There is a high likelihood that the design control will detect a potential failure mode or a future cause of failure.	4
High	It is highly probable that the design control will be capable of identifying a potential failure mode or a subsequent failure cause.	3
Very high	There is a very high likelihood that the design control will detect a likely cause of failure or a future mode of failure.	2

Table 2.4 Scalability of detection. (continued)

Detection	Criteria: likehood of detection by design control	Rank
Almost certain	When design control is implemented correctly, it is highly probable that it will be able to identify a potential failure mode or a future failure cause.	1

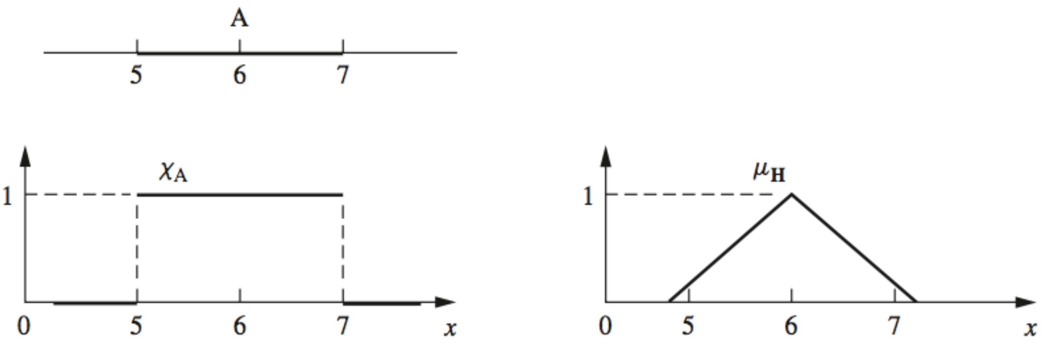
2.5 Fuzzy Thoery

2.5.1 Fuzzy set

The fuzzy set has become a crucial technique in the field of artificial intelligence due to its capacity to replicate the unpredictability of human behavior on a computer while ensuring specific performance. Fuzzy sets have achieved substantial advancements in both research and practical applications in the realm of intelligent computing. The incorporation of fuzzy set theory is crucial for the rapid advancement of fuzzy control and is inseparable from it. Dubois (1980) states that the fuzzy set theory provides novel scientific reasoning and methodology for information science and cognitive science, as well as a practical approach for the advancement of intelligent information processing technology. Since then, numerous experts have dedicated a substantial amount of time and effort to analyzing fuzzy numbers. The utilization of fuzzy numbers in mathematical modeling is an invaluable tool that may be employed to describe uncertainty and analyze information that is ambiguous or subjective. Their potential for expansion is extensive, and they have been applied to address a diverse array of practical challenges, such as fuzzy optimization, fuzzy transportation problems, and fuzzy differential equations (Ebrahimnejad, 2016).

2.5.2 Membership functions

Zadeh (1965) expanded the notion of binary membership to incorporate several levels of membership within the continuous interval [0,1]. In Fig. 2.2 (a), the value of 0 represents no membership, whereas the value of 1 represents complete membership. The indicator function is applicable to discrete sets, but it may not be suitable for representing the different degrees of membership of an element X in a set that can have an infinite number of values over the universe. Despite the function's effectiveness on discrete sets, this remains the case. Zadeh refers to the sets that exist in universe X as fuzzy sets. Fuzzy sets are composed of membership functions, as seen in Fig. 2.2 (b). The membership function is a crucial differentiation between crisp sets and fuzzy sets. A crisp set is characterized by a solitary membership function, but a fuzzy set can be described by an infinite number of membership functions. It is feasible to alter the membership function of fuzzy sets, allowing them to become more adaptable and compensate for their lack of distinctiveness. Fuzzy sets are advantageous for a multitude of diverse applications.



(a)

(b)

Figure 2.2 Membership functions for (a) a crisp set A, (b) a fuzzy set H.
Source: Jomthong (2023)

The fundamental functions utilized in the construction of fuzzy logic include the triangle function, Gaussian function, trapezoidal function, extended bell function, sigmoid function, and the Left-Right (LR) membership function (Jomthong, 2023). This study provides a concise description of the triangular, Gaussian, and trapezoidal membership functions.

A triangular membership function is a mathematical function that is used to represent the membership of an element in a fuzzy set. It is characterized by a triangular shape, with the peak of the triangle representing the maximum membership value.

The utilization of straight lines is employed to produce membership functions that are characterized by their simplicity and ease of comprehension. The triangle membership function, also referred to as TRIMF due to its function name, is the most basic one. The essence of it is just the assemblage of three points that collectively constitute a triangle. Mandal et al. (2012) provide a visual representation of the triangle membership function, which may be seen in Fig. 2.3.

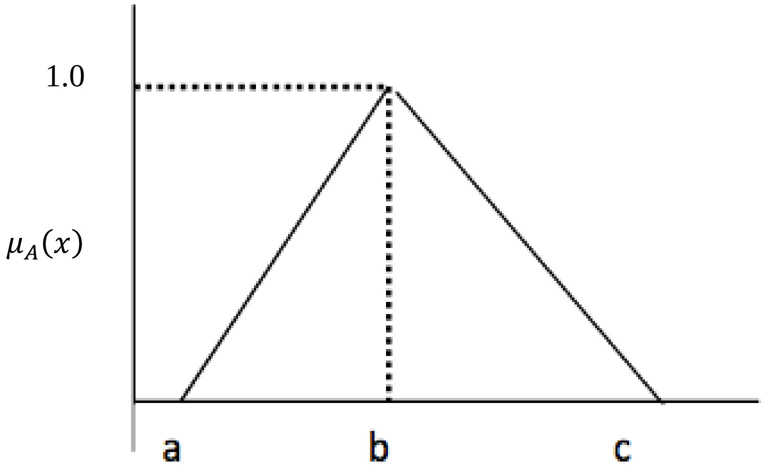


Figure 2.3 Triangular membership function.
Source: Mandal et al. (2012)

$$\mu(x) = \begin{cases} \dfrac{x-a}{b-a} & if\ a \le x \le b \\ \dfrac{c-x}{c-b} & if\ b \le x \le c \\ 0 & if\ x \le a\ or\ x \ge c \end{cases} \tag{2.5}$$

Jomthong (2023) defines the Gaussian membership function as Gaussian (x: c, s), where c represents the mean and s represents the standard deviation. Refer to Fig. 2.4.

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Figure 2.4 Gaussian membership function.

Souce: Jomthong (2023)

$$\mu(x,c,s,m) = exp\left[-\frac{1}{2}\left|\frac{x-c}{s}\right|^{m}\right] \tag{2.6}$$

The trapezoidal membership function is defined by four parameters: a lower limit (a), an upper limit (d), a lower support limit (b), and an upper support limit (c). Please refer to Fig. 2.5 for visual representation.

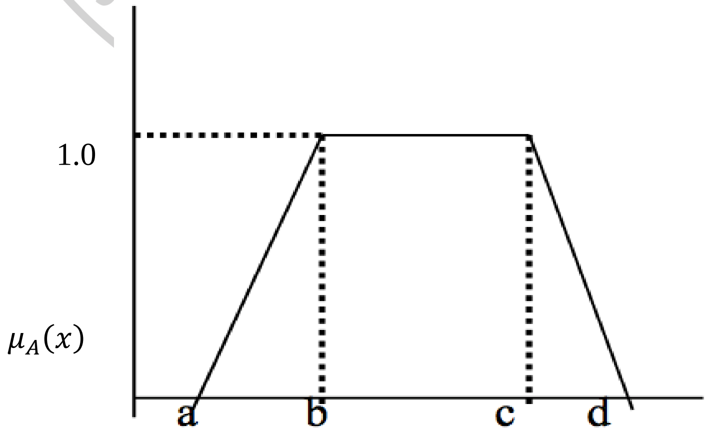

Figure 2.5 Trapzoidal membership function.

Souce: Jomthong (2023)

$$\mu(x) = \begin{cases} 0, & (x < a)\ or\ (x > d) \\ \dfrac{x-a}{b-a}, & a \le x \le b \\ 1, & b \le x \le c \\ \dfrac{d-x}{d-c}, & c \le x \le d \end{cases} \tag{2.7}$$

2.6 Related Studies

Hola and Szostak (2014) constructed a modified EUROSTAT accident model, a thorough general model of the development of an accident situation. The model allows for tracking many potential arrangements of events in accident processes within the construction sector and identifying the most likely sequence of events.

Al-Anbari et al. (2015) devised the RASH approach for building construction to categorize hazards into two main types: Safety hazards and Health Risks. A total of 11 indicators indicating safety hazards and eight factors indicating health hazards were identified from a field survey conducted in Oman. A total of 40 Safety and Health specialists participated in conducting risk assessment using the current risk analysis method (RA) and the new RASH method. The RASH method was more accurate than the conventional RA method for assessing risk zones. The precision achieved by the RASH method was nearly double that of the RA method. The total accuracy rates for the four scenarios using the RASH approach and the RA method were 72.5% and 40%, respectively. The suggested RASH approach exhibited superior error reduction compared to the existing RA method across all circumstances. The existing RA technique was found to have the biggest overestimation of hazards in two specific circumstances, which were identified as the most troublesome. The Wilcoxon Ranked Test revealed a significant difference between the two techniques. The newly developed RASH approach is statistically valid and has demonstrated superior performance in evaluating risk compared to the RA method.

Orji et al. (2016) examined the various types of hazards present in construction sites and their frequency of occurrence. The objective is to raise awareness and promote cautious behavior while suggesting safety measures to mitigate these hazards. The literature examined various types of hazards in building construction sites and the corresponding safety measures to mitigate them. The field survey utilized a questionnaire to determine the frequency of hazards on-site. This survey was conducted using convenience sampling techniques within the Enugu metropolis in Enugu state. Descriptive analytic tools were employed for analysis. The data indicate that equipment-related hazards are frequently seen on site, while electrical hazards are hardly encountered. The report established a conclusion and provided recommendations based on the findings.

Raheem and Issa (2016) outlined a case study conducted to enhance construction safety in Pakistan. The study aimed to develop a framework for implementing safety practices and addressing the perceptual gaps related to safety among stakeholders and regulatory authorities. The suggested safety framework consists of instructions for a mutually beneficial safety implementation system, incorporating legislative advancements and improvements in company safety culture. The framework underwent analysis through the Delphi technique, and priorities were established based on ratings and rankings provided by a panel of Pakistani construction safety experts. The primary focus of this framework is to make every feasible effort to reduce safety risks for construction workers by implementing stricter regulations and encouraging voluntary compliance from all parties involved. This case study can serve as a paradigm for other developing countries to enhance their building safety environment.

Amiri et al. (2017) presentd the development of a fuzzy probabilistic rule-based expert system for assessing occupational hazards. A fuzzy probabilistic system allows us to represent uncertainties associated with accident datasets and the stochasticity resulting from environmental, ecological, or temporal variations. Incorporating stochastic elements into evaluating occupational risks in the construction sector allows authorities to manage hazards proactively, leading to several tangible advantages. The proposed fuzzy probabilistic model utilizes a rule base derived from fuzzy risk-based statistical and data mining studies of accident databases, as well as thorough literature research and expert interviews. This model undergoes testing using four significant building case studies. After a rigorous validation process, the model was effectively examined, and rankings were assigned to various categories of hazards. The results are promising, and the model can be used in many construction projects.

CHAPTER 3
RESEARCH METHODOLOGY

This chapter presents the research method to apply a hybrid fuzzy multi-criteria decision technique to assess the occupational hazard of a sample construction company. Section 3.1 shows the calculation steps of the proposed technique. Section 3.2 explains the sample construction company. Section 3.3 illustrates the research procedure.

3.1 Research Design

This section focuses on the calculation steps of the proposed occupational hazard assessment technique. There are six steps as follows.

3.1.1 Network diagram building step

The network diagram is based on the analytic network process concept which an element in a cluster can affects to another element in the same or different clusters. Figures 3.1 shows the network of causes-and-effect of this study. Please note that the acronyms are pre-determined dominant hazard factors and causes (G1 and G2), Construction functions (CF), Hazard factors (HF), and Hazard causes (HC).

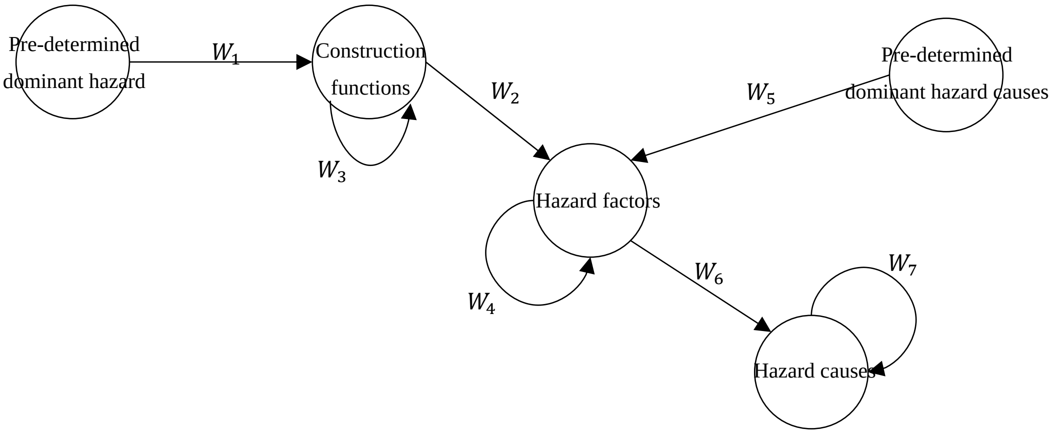

Figure 3.1 Analytic network diagram.

3.1.2 Super-matrix generating step

The super-matrix is constructed as follow.

$$
\begin{array}{c|ccccc|}
 & \text{G1} & \text{G2} & \text{CF} & \text{HF} & \text{HC} \\
\text{G1} & 0 & 0 & 0 & 0 & 0 \\
\text{G2} & 0 & 0 & 0 & 0 & 0 \\
\text{CF} & W_1 & 0 & W_2 & W_3 & 0 \\
\text{HF} & 0 & W_5 & 0 & W_4 & W_6 \\
\text{HC} & 0 & 0 & 0 & 0 & W_7
\end{array}
\tag{3.1}
$$

where W_1 is the relative important construction functions with respect to pre-determined dominant hazard factors, W_2 is the inner dependent construction factors, W_3 is the outer dependent construction factors and hazard causes, W_4 is the inner dependent hazard factors, W_5 is the relative important hazard factors with respect to pre-determined dominant hazard causes, W_6 is the outer dependent hazard factors and hazard causes, and W_7 is the inner dependent hazard causes.

3.1.3 Elements' weight calculation step

This step uses fuzzy pairwise comparison based on the analytic hierarchy process method. The linguistic variables are translated into triangular fuzzy numbers (TFNs). The numbers and their definitions are illustrated in Table 1. Please note that the seven-level scale is used in the AHP instead of the ten-level scale. The seven-level comparison scale includes absolutely unimportant (1/9,1/7,1/3), strongly unimportant (1/7,1/5,1/3), weakly unimportant (1/5,1/3,1), equally important (1,1,1), weakly important (1,3,5), strongly important (3,5,7), and absolutely important (5,7,9).

Suppose that one column of a submatrix contained m elements. Accordingly, the pairwise comparison matrix for m elements can be represented by $E = \left[\tilde{e}_{ij}\right]_{m\times m}$, which $\tilde{e}_{ij} = 1/\tilde{e}_{ji}$. Then, each column is derived by using Eq. (3.2).

$$\widetilde{w}_i = \frac{\left(\prod_{j=1}^{m} \tilde{e}_{ij}\right)^{1/m}}{\sum_{i=1}^{m}\left(\prod_{j=1}^{m} \tilde{e}_{ij}\right)^{1/m}}, \quad \forall i, j \in \{1,2,..,m\} \tag{3.2}$$

where $\widetilde{w}_i$ is the fuzzy weight of the element i in a column of a submatrix, and $\widetilde{w}_i = (w_i^a, w_i^b, w_i^c)$, $\forall i \in \{1,2,\ldots,m\}$. Please note that w_i^a, w_i^b, and w_i^b are the smallest, most, and largest likely values, respectively. The pairwise comparison matrix E is, then, tested the consistency by performing critical value calculation by using Eq. (3.3) to (3.5).

$$\lambda_{max} = \frac{1}{m}\left(\sum_{i=1}^{m}\left(\frac{\sum_{j=1}^{m} e_{ij}^k w_i^k}{w_i^k}\right)\right), \quad \forall i, j \in \{1,2,\ldots,m\} \tag{3.3}$$

$$CI = \frac{\lambda_{max} - m}{m - 1} \tag{3.4}$$

$$CR = \frac{CI}{RI} \tag{3.5}$$

λ_{max} is the largest eigenvalue of the matrix E, CI is the consistency index, and RI is the random index which can be found in Winston (2004), see Table 3.1. If the CR is lower than 0.1, the matrix E is consistency and acceptable.

Table 3.1 Random index numbers.

n	RI
1	0.000
2	0.000
3	0.580
4	0.900
5	1.120
6	1.240
7	1.320
8	1.410

Table 3.1 Random index numbers. (continued)

n	RI
9	1.450
10	1.490
11	1.510
12	1.480
13	1.560
14	1.570
15	1.590
16	1.605
17	1.610
18	1.615
19	1.620
20	1.625

3.1.4 Relative importance of hazard factors and causes calculation step

The limit matrix is calculated by determining $\lim_{n\to\infty} E^n$. However, in this study, the hazard-factor interdependent weight can be obtained by $W_{HF}^{I} = W_4 \times W_2$. The construction-function interdependent weight can be obtained by $W_{CF}^{I} = W_3 \times W_1$. The hazard-factor weigh, lastly, can be calculated as $W_{HF} = W_{HF}^{I} \times W_{CF}^{I}$. Next, the hazard-cause weight is calculated by $W_{HC} = (W_7 \times W_6) \times (W_4 \times W_5)$. Please note that since the values in the matrix are crisp values, we used the TFNs operations in these steps.

3.1.5 Fuzzy ordering step

The W_{HF} and W_{HC} are denoted by TFNs. The fuzzy ordering formula is used.

$$R(\tilde{A}) = \sqrt{\frac{\frac{(b-a)^3}{4} + \frac{(b-a)a^2}{2} + \frac{2(b-a)^2 a}{3} + \frac{(c-b)^3}{12} + \frac{(c-b)b^2}{2} + \frac{(c-b)^2 b}{3}}{3(c-a)}} \tag{3.6}$$

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where $R(\tilde{A})$ is the area of a TFN $\tilde{A} = (a, b, c)$. For any two $\tilde{A}_i$ and $\tilde{A}_j$, 1) if $R(\tilde{A}_i) < R(\tilde{A}_j)$, then $\tilde{A}_i < \tilde{A}_j$, 2) if $R(\tilde{A}_i) = R(\tilde{A}_j)$, then $\tilde{A}_i = \tilde{A}_j$, and 3) if $R(\tilde{A}_i) > R(\tilde{A}_j)$, then $\tilde{A}_i > \tilde{A}_j$.

3.1.6 Fuzzy risk priority number calculation step

There are three sub-steps to calculate the fuzzy-RPNs: 1) fuzzy-rule base construction, 2) fuzzy inference, and 3) defuzzification. The first sub-step depends on the expert to construct the rule based on his experience. Figure 3.2 shows the general rule base. The linguistic variables and their definitions are shown in Tables 3.2 and 3.3. The second sub-step uses Eq. (3.7) and (3.8) to discover the risk level of $\tilde{A}$.

Rule i: If Occurrence is $\tilde{A}_{i1}$
and Severity is $\tilde{A}_{i2}$
and Not detection $\tilde{A}_{i3}$
then R is priority number is $\tilde{C}_i$.

Figure 3.2 Rule-base method for FMEA.

Table 3.2 Linguistic variables.

Linguistic variables	Fuzzy numbers	Occurrence (O)	Severity (S)	Detection (D)
Very low (VL)	(0, 0, 0.2)	Rare incidence	No fatality	Always detectable
Low (L)	(0.1, 0.3, 0.5)	Once for a long time	No absent injury	A very high probability to detect
Moderate (M)	(0.3, 0.5, 0.7)	More than one occurs	One-day absent injury	A moderate probability to detect
High (H)	(0.5, 0.7, 0.9)	More frequent than one	More than one-day absent	A small probability to detect
Very high (VH)	(0.8, 1, 1)	Several times	Fatal of employee	Impossible to detect

Table 3.3 Linguistic variables of risk priority numbers.

Linguistic variables	**Fuzzy numbers**	**Risk priority number (RPN)**
Very low (VL)	(0, 0, 0.2)	The hazard risk is minimal, and there is little need for preventive or remedial measures.
Low (L)	(0.1, 0.3, 0.5)	The hazard risk is low and acceptable; thus, no prevention or improvement is needed.
Moderate (M)	(0.3, 0.5, 0.7)	The hazard risk is moderate and acceptable. However, general prevention and improvement are needed.
High (H)	(0.5, 0.7, 0.9)	Th hazard risk is considerable, so prompt preventative and improvement measures are needed to increase monitoring and reduce risk.
Very high (VH)	(0.8, 1, 1)	The hazard risk is extremely high, necessitating the immediate cessation of building until the risk is mitigated.

$$\mu(y)_{\tilde{C}_i'} = \min\left[\alpha, \mu(y_i)_{\tilde{C}_i}\right], \ \ \forall i \in \{1,2,\dots,m\} \tag{3.7}$$

$$\alpha = \min\left[Hight\left[\tilde{A}_i \cap \tilde{A}_j\right]\right] \tag{3.8}$$

where $\mu(y)_{C_i}$ is the membership function of the derived risk $\widetilde{C'}_i$ for rule $i, \forall i \in \{1,2,\dots,m\}$, is the membership function of the assigned risk $\tilde{C}_i$ for rule $i, \forall i \in \{1,2,\dots,m\}$, and α = the minimum height for the intersected results. The aggregated outputs $\tilde{C}$ from all rules is then $\tilde{C} = \tilde{C} \cup \tilde{C} \cup \cdots \cup \tilde{C}$, where $\tilde{C}$ is the aggregated risk level of a failure mode.

The third sub-step defuses the TFNs using the center of gravity method as shown in Eq. (3.9).

$$y^* = \frac{\int y \cdot \mu_{\tilde{C}}(y)}{\int \mu_{\tilde{C}}(y)} \tag{3.9}$$

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where y^* is the defuzzification value of the risk $\tilde{C}$ and $\mu_{\tilde{C}}(y)$ is the membership function of the risk $\tilde{C}$.

3.2 A Case Studty

A construction site in Kunming was a field study of this research. The occupational health and safety supervisor participated in this study. The construction site is a residential building. However, the size and its location are confidential. There are ten functions in the construction phase: site clearing (CF1), laying the foundation (CF2), plinth beam and slab (CF3), superstructure (CF4), bricklaying (CF5), lintel and roof coating (CF6), plumbing and electrical wiring (CF7), exterior and interior jobs (CF8), flooring (CF9), and painting (CF10). Table 3.4 shows the functions and their codes.

The supervisor identified 11 hazard factors corresponding to the construction steps. The causes were pointed out as follows: unsafe environment (C1), substandard construction site (C2), substandard facility (C3), protective gear (C4), equipment and tools (C5), work procedure (C6), coordination and communication (C7), and personal health (C8). Table 3.5 shows the hazard factors and Table 3.6 shows the hazard causes of this study.

Table 3.4 Construction functions.

No.	Construction function	Code
1	Site clearing	CF1
2	Laying the foundation	CF2
3	Plinth beam and slab	CF3
4	Superstructure	CF4
5	Bricklaying	CF5
6	Lintel and roof coating	CF6
7	Plumbing and electrical wiring	CF7
8	Exterior and interior jobs	CF8
9	Flooring	CF9
10	Painting	CF10

Table 3.5 Hazard factors.

No.	Construction function	Code
1	Working at heights	HF1
2	Moving objects	HF2
3	Slips and trips	HF3
4	Noise	HF4
5	Hand arm vibration syndrome	HF5
6	Material handling	HF6
7	Excavations	HF7
8	Asbestos	HF8
9	Electricity	HF9
10	Airborne fibers and materials	HF10
11	Site security	HF11

Table 3.6 Hazard causes.

No.	Construction function	Code
1	Unsafe environment	C1
2	Substandard construction site	C2
3	Substandard facility	C3
4	Protective gear	C4
5	Substandard construction equipment and tools	C5
6	Work procedure	C6
7	Coordination and communication	C7
8	Personal health	C8

Our study process is structured around a six-step procedure, detailed in section 3.1. The first step, illustrated in Fig. 3.1, is followed by the generation of a super-matrix, which relies on a comparison questionnaire. The supervisor used the questionnaire, a vital tool in our research, to conduct 55 pairwise comparisons of the hazard factors. The questionnaire was designed under the supervision of the thesis advisor. However, we did not conduct any research tool evaluation due to the confidentiality we committed with the sample company management. Table 3.7 shows the example of a submatrix W_1.

Table 3.7 Parts of questionnaire for submatrix W_1.

	AU	SU	WU	EI	WI	SI	AI
HF1 vs HF2					✓		
HF1 vs HF3						✓	
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
HF9 vs HF11				✓			
HF10 vs HF11							✓

Other matrices were conducted in the same manner. The super-matrix was built as Eq. (3.1). The weights of elements are calculated using Eq. (3.2). The matrix was consistency tested using Eq. (3.3) to (3.5). The relative importance of hazard factors and causes was calculated. We can rank the HF, CF, and C using (3.6). Finally, the fuzzy-RPNs can be calculated using Eq. (3.7) to (3.9).

3.3 Research Procedure

The research process is show in Fig. 3.2.

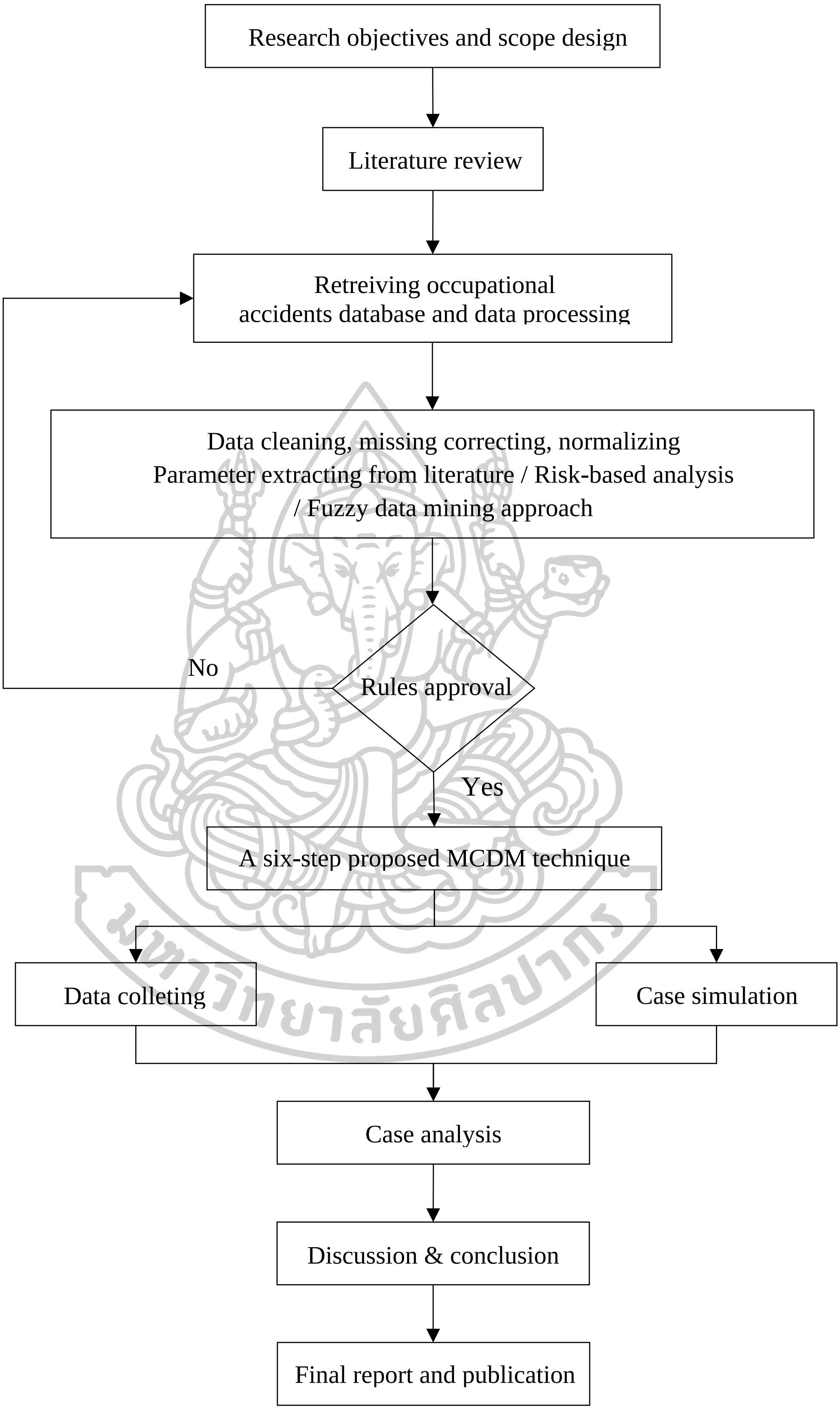

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Figure 3.3 Research procedure.

CHAPTER 4
RESULT AND ANALYSIS

This chapter presents the research results and its findings. The illustrations avoid to show the cumbersome calculation which occurred in a spreadsheet. We only show its results and making the discussion based on the finding. Furthermore, we would like to discuss about the proposed technique by comparing with a conventional tool.

4.1 Ranking

The HF, CF, and C vectors are shown below.

$$W_{HF} = \begin{bmatrix} (0.038,0.079.0.576) \\ (0.044.0.070,0.432) \\ (0.038.0.057.0.417) \\ (0.017,0.032,0.178) \\ (0.037,0.055,0.410) \\ (0.045,0.068,0.421) \\ (0.030,0.049,0.399) \\ (0.042,0.066,0.422) \\ (0.033,0.050,0.398) \\ (0.029,0.047,0.215) \\ (0.015,0.029,0.160) \end{bmatrix}$$

$$W_{CF} = \begin{bmatrix} (0.014,0.063,0.199) \\ (0.015,0.066,0.198) \\ (0.017,0.070,0.277) \\ (0.020,0.096,0.295) \\ (0.016,0.065,0.270) \\ (0.022,0.075,0.284) \\ (0.014, 0.077,0.235) \\ (0.013,0.064,0.169) \\ (0.012,0.063,0.170) \\ (0.012,0.058.0.166) \end{bmatrix}$$

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$$W_C = \begin{bmatrix} (0.006,0.048,0.543) \\ (0.007,0.069,0.648) \\ (0.007,0.056,0.633) \\ (0.009,0.085,0.897) \\ (0.009,0.076,0.788) \\ (0.006,0.032,0.497)) \\ (0.004,0.139,0.292) \\ (0.004,0.275,0.324) \end{bmatrix}$$

The ranking of attributes is shown in Table 4.1.

Table 4.1 Ranking result of hazard factors, construction functions, and causes.

Hazard factors	Risk level	Ranking	Construction	Risk level	Ranking	Causes	Risk level	Ranking
HF1	0.1067	1	CF1	0.0408	7	C1	0.0953	5
HF2	0.0826	2	CF2	0.0411	6	C2	0.1148	3
HF3	0.0782	5	CF3	0.0546	3	C3	0.1111	4
HF4	0.0343	10	CF4	0.0607	1	C4	0.1578	1
HF5	0.0768	6	CF5	0.0528	4	C5	0.1389	2
HF6	0.0807	3	CF6	0.0568	2	C6	0.0861	7
HF7	0.0737	8	CF7	0.0483	5	C7	0.0639	8
HF8	0.0804	4	CF8	0.0360	8	C8	0.0869	6
HF9	0.0739	7	CF9	0.0359	9	-	-	-
HF10	0.0431	9	CF10	0.0347	10	-	-	-
HF11	0.0308	11	-	-	-	-	-	-

Table 4.1 shows the most critical hazard factor is ‘working at height’. The second order of the hazard factors is ‘moving objects.’ The least important hazard factor is ‘site security.’ The most important construction function is ‘superstructure.’ The second order is ‘lintel and roof coating.’ The least essential construction function is ‘painting.’ The most crucial cause is ‘protective gear.’ The second important order is ‘equipment and tools.’ The least essential cause is ‘coordination and communication.’

4.2 Risk Priority Numbers

The RPNs are calculated by using three sub-steps in step 6. The rule base is constructed by the occupational health and safety supervisor. The ranking of hazard factors by considering the risk priority numbers compared to the conventional FMEA method is shown in Table 4.2.

Table 4.2 Comparison between fuzzy-FMEA and conventional FMEA.

Hazard factors	Fuzzy-FMEA	Conventional FMEA
HF1: working at heights	1	1
HF2: moving objects	2	5
HF3: slips and trips	5	8
HF4: noise	10	9
HF5: hand arm vibration syndrome	6	7
HF6: material handling	3	4
HF7: excavations	8	2
HF8: asbestos	4	10
HF9: electricity	7	6
HF10: airborne fibers and materials	9	11
HF11: site security	11	3

Table 4.2 shows that the ranking results of hazard factors from fuzzy-FMEA and the conventional FMEA differ. The first rank, ‘working at height,’ is the only factor that is the same.

Conventional FMEA often uses the risk priority number (RPN) to ascertain the risk priorities of failure modes. The RPN is generated by multiplying the probability of occurrence (O), the severity of the failure (S), and the likelihood of failure detection (D). Nevertheless, this computational approach has faced criticism for multiple reasons. For example, the relative significance of the three components (O, S, and D) needs to be taken into account; the value of RPN may not be the product of these three factors, and accurately estimating the three factors is challenging. In order to address the limitations above, this study employed the fuzzy inference approach to calculate the Risk Priority Number (RPN) instead of the multiplication of the three components.

This study deployed muti-criteria decision-making tools to assess occupational hazards in construction projects. Due to the problematic and substantial construction sites, safety management in construction is a challenge. The conventional FMEA is modified using the concepts of the analytic network process, the analytic hierarchy process, the fuzzy rule base, and fuzzy inference to obtain more reasonable risk factors. The case study showed that the priority hazard factor was 'working at height' while the priority was 'protective gear.' The results were different from the conventional FMEA. Finally, the assessment results can be used to form the occupational hazard mitigation strategy for the construction site.

4.3 Discussion

The proposed occupational hazard assessment tool combines several multi-criteria decision-making tools. Thus, we cannot claim that this proposed idea is a hybrid of primary techniques. It started with the analytic network, which considers the direct effect of elementary factors and the indirect effect of side ones. Furthermore, the functions and causes are included in the analysis. The super-matrix is the idea of the analytic network process based on the analytic hierarchy process. Consistency evaluations are still needed in this step. Three steps, fuzzy-rule base construction, fuzzy inference, and defuzzification, were deployed to cope with fuzzy risk priority numbers. The fuzzy-baed technique makes the risk priority numbers easy to receive. Three parameters of RPN are reasonably quantifying.

CHAPTER 5
CONCLUSION

This chapter concludes the findings of the last chapter. We will not rephrase the result in chapter 4. However, we would like to conclude the occupational hazard assessment tool's performance according to the objective, section 5.1. In addition, the drawbacks of the proposed technique are pointed out in section 5.2. Section 5.3 gives the research directions for an interested researcher.'

5.1 Conclusion according to Objective

The proposed technique considered construction functions, hazard factors, and causes simultaneously. This character is outstanding in other occupational hazard assessment tools. The failure mode and effects analysis-based tool make the results easy to understand. However, giving the number of three parameters, failure probability, failure severity, and the power of detection, is painful. The fuzzy technique alleviates this cumbersome. However, the calculation steps are the drawbacks of the proposed technique. Several pairwise comparisons are needed. In addition, the calculation steps are based on large-dimension matrices. As a result, a skilled analyst is needed to conduct the data analysis step. In practice, it is aching.

5.2 Recommendations

As mentioned in the last section, the drawback of this occupational hazard assessment technique is the large-dimension matrix operations. Moreover, the data analysis requires a skilled analyst. It is good to have a computer package that calculates these steps specifically.

5.3 Interesting Research Directions

The first direction is to code a computer package for the proposed occupational hazard assessment tool. The second direction is to integrate the hazard mitigation cost into the analysis. The result should be the recommended hazard factor, construction function, and cause mitigation strategies at a reasonable cost.

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