DEVELOPMENT OF A RISK ASSESSMENT METHODOLOGY AND SAFETY MANAGEMENT MODEL FOR THE BUILDING CONSTRUCTION INDUSTRY: CASE STUDIES FROM THAILAND

by

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ABSTRACT

The building construction industry is growing all over the world and considered as a labour-intensive industry. It is associated with significant safety risks and losses resulting from major accidents. These critical safety risks are largely due to ignorance or lack of awareness, which causes poor performance in building construction activities. Furthermore, it is difficult to estimate the safety risks because of the incomplete quantitative safety risk database and uncertainty within construction projects. Most of the safety risk assessment tools which are employed in the construction domain may not produce adequate outcomes, since it may not be easy to evaluate a hazardous event quantitatively in a safety risk assessment, as the lack of information in the safety risk database makes it difficult to determine whether there is an opportunity for a possible consequence to occur. Moreover, in construction management projects, risk assessment tools are still widely employed by adopting two traditional parameters, severity of consequence (SC) and probability of occurrence (PO), to analyse the safety risk level. It is not clear, however, whether this analysis can evaluate the safety risk magnitude appropriately, which necessitates the introduction of another parameter, probability of consequence (PC), to improve the risk evaluation. Therefore, this study aims to provide an effective tool to develop safety risk and management measures to reduce injuries and improve the safety of workers within the building construction industry.

The findings of the study show that the fuzzy reasoning technique (FRT), based on the fundamentals of fuzzy sets and fuzzy logic, is useful for quantifying and dealing effectively with the lack of certainty, subjectivity, badly defined challenges, and vagueness related to the domain of building construction projects and other fields. PC was incorporated into the model which allows safety risks to be assessed correctly. Furthermore, the modified fuzzy analytical hierarchy process (MFAHP) and fuzzy technique for order preference by similarity to ideal solution (FTOPSIS) methods are integrated into a new construction safety risks model to be ranked based on management priorities for the evaluation of important safety risks. Four specific case studies are employed to illustrate the applicability and performance of the proposed model. This research contributes significantly to construction safety management projects and can be utilised to analyse and manipulate the safety risk level of every possible hazardous event that is identified during the construction period. The proposed model could also be applied in other construction projects to obtain results with greater accuracy and reliability from the evaluation and ranking of safety risks, which would yield data that would be useful in helping the management team to mitigate and control the risks in other construction projects.

DEDICATION

This thesis is dedicated to my family who have been a constant source of all their love, encouragement and support during the challenge of my studying in the UK.

Above all this thesis is also dedicated to: The sake of Allah, my Creator and my Master. My great teacher and messenger, Muhammad (May Allah bless and grant him), who enlightened the purpose of our life.

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LIST OF PRINCIPAL ABBREVIATIONS

A	Acceptable Risk
AHP	Analytical Hierarchy Process
CC	Closeness Coefficient
CDM	Construction (Design and Management) Regulations
CHA	Concept Hazard Analysis
CO	Collapse of Site Structure
CS	Confined Spaces
EFA	Equivalent Fatality Analysis
EH	Ergonomic/Human Factors
EL	Electricity
EM	Equipment, Machinery, Tools
ES	Exposure to Hazardous Substances
ETA	Event Tree Analysis
FAHP	Fuzzy Analytical Hierarchy Process
FE	Fire and Explosions
FH	Falls from Height
FMEA	Failure Mode and Effects Analysis
FO	Falling Objects
FRT	Fuzzy Reasoning Technique
FTA	Fault Tree Analysis
FTOPSIS	Fuzzy Technique for Order Preference by Similarity to Ideal Solution
H	High Risk
HAZOP	Hazard and Operability study
HSE	Health and Safety Executive
IHA	Inherent Hazard Analysis
ILO-OSH	Guidelines on Occupational Safety and Health Management Systems
JHA	Job Hazard Analysis
L	Low Risk
MCDM	Multiple Criteria Decision Making

MCS	Monte Carlo Simulation
MFAHP	A Modified Fuzzy Analytical Hierarchy Process
MF_f	Membership Function
MH	Manual Handling
NV	Noise and Vibration
OH&S	Occupational Health and Safety
OHSAS	Occupational Health and Safety Assessment series
PC	Probability of Consequence
PHA	Preliminary Hazard Analysis
PO	Probability of Occurrence
PPE	Personnel Protective Equipment
RH	Radiation Hazards
RL	Risk Likelihood
RM	Risk Magnitude
RS	Risk Severity
SC	Severity of Consequence
SSOP	Safety Standard Operation Procedure
ST	Slips and Trips
STFN	Standardized Trapezoidal Fuzzy Number
TH	Traffic Hazards
TOPSIS	Technique for Order Preference by Similarity to Ideal Solution
U	Unacceptable Risk
V	Average Risk
VO	Vehicle Overturn
WF	Weight Factor
Q3/2016	The third Quarter in 2016

CHAPTER ONE

INTRODUCTION

1.1 Introduction

The construction industry has a poor record on safety risk management in comparison to other industries, and construction sites are dangerous places (Carr and Tah, 2001; Carter and Smith, 2006; Zeng et al., 2007; Fung et al., 2010; Nieto-Morote and Ruz-Vila, 2011; Sherratt et al., 2013; Sousa et al., 2014) because of their high accident, injury and fatality rates. The risks of fatal accidents in the construction industry are five times more probable than in other industries (Sawacha et al., 1999). Although the number of fatal occupational accidents in the construction industry worldwide is difficult to quantify as information on this issue is not available for many countries, it is reasonable to expect that at least 55,000 deaths occurred every year on construction sites (Adane et al., 2013). Compared to many other activities in other industry sectors, construction activities are more dangerous due to the unique features of construction work, for example, the high-risk characteristics of construction activities, which include steel erection, demolition, scaffolding, excavation, falsework or temporary framework, maintenance, roof work, and site transport when people work at complex work sites. Specifically, the most frequent hazards, such as falls from height, falling objects and materials, electricity, trips, asbestos, manual handling, noise and vibration, chemicals, and, mobile plants, in construction projects identified by the Health and Safety Executive (HSE) in Britain in 2011 (HSE, 2011) provide useful information for risk analysis. Thailand's construction development has risen significantly and rapidly in recent years (Aksorn and Hadikusumo, 2008). The construction industry in Thailand is still unable to treat safety and health as important issues, however. Although there have been improvements, progress is slow compared to other countries. Safety programmes offering a proactive approach are one of the best ways to improve site safety performance (Tam et al., 2004). An effective safety programmes can considerably reduce accidents as it can help management to develop safer methods of operation and create a safer workplace for the employees (Abdelhamid and Everett, 2000). Therefore, it is essential to create construction safety risk management schemes that can be used to evaluate the relative effectiveness of safety programmes based upon the activities expected for a given process. Furthermore, determining the probability and severity of risk for the employees' activities associated with a task and defining the probability and severity reduction values resulting from the implementation of various safety programme elements should be studied to improve the occupational safety management in building construction.

In recent years, there has been an increase in the use of risk assessment and occupational safety management mechanisms for safety. Risk assessment is becoming increasingly important for construction industries (Zeng et al, 2007). Many companies have installed safety management systems for monitoring safety, and efforts have been made to improve safety. Tam et al., (2002, cited in Gürcanli and Müngen, 2009, p.372) suggest that in every case, the primary importance of safety practices is the risk analysis and hazard assessment. Moreover, the assessment of risk is a complex subject shrouded in vagueness and uncertainty. Ambiguity is unavoidable as safety experts tend to assess the risks for the workers in the construction industry in terms of linguistic expressions rather than metrics.

A recent study shows that risk assessment and management is one of the most important stages in the success of a project. Regarding the UK, Zeng et al., (2007) state that due to the inherent risks, risk analysis in construction projects, especially in the early stages, is often affected by many factors, including human error and vague information.

Therefore, construction project safety risk assessment has been recognised as an important issue in the safety risk management process to identify and assess the potential safety risks. Safety risk mitigation measures must be applied by reducing the probability of occurrence or controlling the possible consequence if a hazardous event has been identified and analysed as having a high risk level. In many circumstances, safety risk assessment approaches, such as event tree analysis (ETA), fault tree analysis (FTA), failure mode and effects analysis (FMEA), Monte Carlo simulation (MCS), consequence analysis, equivalent fatality analysis (EFA), and sensitivity analysis (Zeng et al., 2007; An et al., 2011; Nieto-Morote and Ruz-Vila, 2011) are widely employed in building construction projects. Nonetheless, the application of these techniques may make it more difficult to determine an adequate level of liability to a satisfactory degree of confidence, as the safety risk data is often incomplete or the information may be inadequate to determine the risk level. Therefore, it is necessary to develop new safety risk assessment and management methods and models that can be used to estimate and assess the safety risks in building construction projects, for example, by using the Fuzzy Reasoning Technique (FRT). The fuzzy reasoning approach, which is based on the principle of fuzzy sets and fuzzy logic, offers advantages which can systematically measure both quantitative as well as qualitative information from available sources to simplify risk analysis. Furthermore, this method can be used to reduce the uncertainties, subjectivity, ill-defined problems, and vague information effectively.

1.2 Statement of the Research Problems

Recently, Thailand's construction industry has been experiencing widespread growth in construction sites, especially in the capital city. Aksorn and Hadikusumo (2008) state that

Thailand's economy and infrastructure development has increased considerably and rapidly. Furthermore, the construction industry continues to play a significant role in the continued development, and construction activities have been implemented to fulfil the high demand for market expansion. With the rise in construction sites, however, the number of construction accidents has also increased. On many building construction sites there are too many unsafe conditions and ill-advised activities are performed. Most employees currently employed in the construction industry are originally from the agricultural sector. Moreover, both construction and agricultural work are characterised by temporary workers who are more likely to split their time between these seasonal jobs during agricultural production and construction (Aksorn and Hadikusumo, 2008). Regarding construction sites in Thailand, Pipitsupaphol and Watanabe (2000, cited in Hamid et al., 2008, p.247) found that an accident do not just happen; they are caused by the workers' carelessness, failure of workers to follow safety procedure, working at high elevation, using equipment without safety devices, harsh job operation, unskilled workers and workers' lack of knowledge, poor attitude of workers, unusual nature of the industry, working site conditions, misuse of equipment, improper loading or placement of equipment, lack of warning for co-workers, failure to secure equipment, failure to use personal protective equipment (PPE), unsafe operations, human elements, and poor site management.

Safety risk management programmes are a key to eliminate occupational accidents and injuries. Siriruttanapruk and Anuntakulnathi (2004 cited in Aksorn and Hadikusumo, 2008, p.711) point out that the low levels of safety in the construction industry in Thailand are mainly due to inadequate implementation of safety and weak enforcement of law. Similarly, Limsupreeyarat et al., (2010) highlight that although safety guidelines, regulations and safety rules have been implemented and enforced, Thai construction safety measures, such as guardrails, safety nets, harness, and safety line systems, are still insufficient. Moreover, the involved parties, namely, construction engineers and supervisors, have not given much attention to the unsafe conditions, which may be due to ignorance and lack of awareness of the personnel's safety concerning hazards and risks.

Based on the statistics in a report about occupational accidents by the Social Security Office (2016), the rapid expansion of Thailand's construction activities has caused a continuing increase in the reported number of accidents. Furthermore, in the construction sector, the category of injury is reported to have the highest number of accident cases (7,129 people in 2016) compared to other sectors. Figure 1-1 shows the statistics on occupational accidents among workers in Thailand during the period 2012-2016 classified by the top five types of establishment. From the statistics, it can be seen clearly that accidents in construction establishments are more serious than in other establishments.

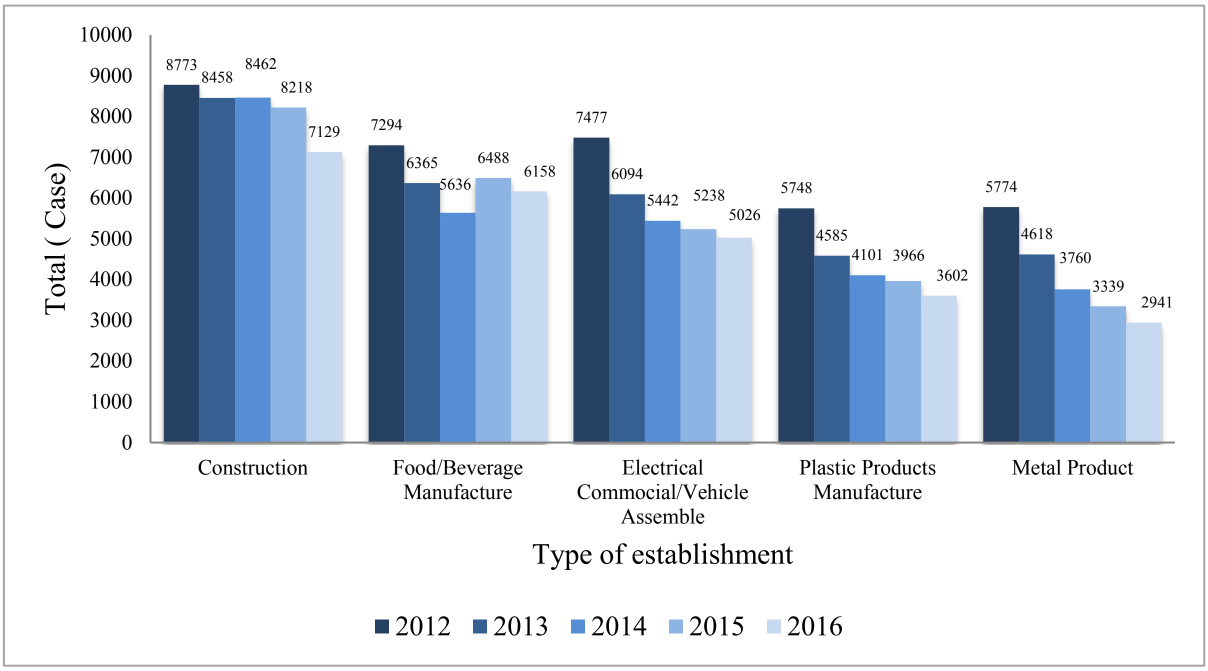


Figure 1-1: Occupational accident and diseases statistics 2012-2016 classified by top five types of establishment in Thailand (Source: Social security Office, 2016)

All the accident records from around Thailand are collected by the Ministry of Labour and Social Welfare to facilitate the processing of compensation requests and other issues. Furthermore, there is improper documentation, and the classification system for the data collection and the cause of industrial accidents in the building construction industry are inadequate. Moreover, the number of unregistered employees in the building construction industry is very high. As a result, many injuries are not recorded or documented appropriately. When conducting safety risk assessments for the building construction industry, there is often insufficient data or vague information available.

In many circumstances, however, there is a high level of uncertainty in the safety risk data (Yildiz at al., 2014). It is not well known how people address hazards and how safety risk information is processed and evaluated. The application of safety risk assessment tools in the building construction industry may not provide good results, as the safety risk information or data has limited the intervention process to improve occupational safety on construction sites in Thailand.

1.3 Aims and Objectives

The research aims to provide an effective tool to develop safety risk and management measures to reduce injuries and improve the safety of workers within the building construction industry.

This will involve the development of a risk assessment and occupational safety management model in building construction for the building construction industry. The research objectives are:

1) To examine the current occupational safety problems and investigate the various types of risk. Data and information on accidents in the industry will be collected from reports, articles, and the industry.
2) To undertake a comprehensive literature review to establish potentially viable research routes. The literature will be reviewed to establish a research framework to complete this research successfully.
3) To identify most of the key possible safety risks in the building construction industry. A questionnaire survey will be used to collect data and confirm the safety risks identified and to find other important risks in the Thai building construction industry.
4) To develop a safety risk management model for a risk assessment and occupational safety management strategy. The information received from the collection of data will then be used to define the standards of qualitative descriptors and develop an associated safety risk management model. Secondary sources will be interpreted and processed for analysis of the safety risk management model.
5) To verify the reliability of risk assessment and occupational safety management models through case studies. This model will be applied in the real construction industry. Case studies will be used to illustrate the application of the proposed safety risk management model.
6) To produce an effective and efficient safety risk assessment and management framework that could be accepted by the Thai building industry. An interview survey will be used to collect data and find out how to manage high risks.

1.4 Research Questions

This study focuses on the practice used for safety risk assessment and management. The overall aim and objectives mentioned in Section 1.3 were developed into specific research questions for this thesis by reviewing the relevant literature on safety risk assessment and management. The research questions are:

Research question 1: Why does the construction industry have a very poor performance in safety risk management?

Research question 2: What techniques and methods can be employed to develop a safety risk management model and deal with the uncertainty in the construction industry?

Research question 3: What are the benefits and implications of implementing safety risk management for handling uncertainties in construction projects?

1.5 Research Novelty

Firstly, in many circumstances, the applications of the current safety risk assessment techniques in the building construction industry use two safety risk parameters, probability of occurrence and severity of consequence, to assess the safety risk magnitude. However, this analysis is insufficient to determine the safety risk level effectively and accurately, which requires the introduction of a third parameter, probability of consequence, to be incorporated into the proposed model to obtain more accurate and reliable results of safety risk analysis.

Secondly, in the previous building construction research, no research has been conducted to study the combination of the FRT, analytical hierarchy process (AHP) and technique for order preference by similarity to ideal solution (TOPSIS) methods to develop a new safety risk management model.

The FRT can be used to assess both quantitative and qualitative risk data and information on building construction projects to reduce the uncertainties, subjectivity, ill-defined problems, and vague information associated with building construction projects and activities. Furthermore, the fuzzy technique for order preference by similarity to ideal solution (FTOPSIS) and a modified Fuzzy Analytical Hierarchy Process (MFAHP) model will be employed to obtain the final ranking for evaluation of important safety risks to support effective safety risk decision-making based on limited resources for managing and controlling safety risks. The results from the proposed safety risk management model can provide final ranking for evaluation of important safety risks in the building construction projects, which can provide useful information for project managers, safety managers and engineers to manage and control risks during building construction projects.

1.6 Research Outcomes

Proper construction risk safety management will be developed in the Thai building construction industry. A new safety risk assessment model should be identified to assess the specific risks. Furthermore, when the research activities have been completed, the findings will be published in journals that are easily accessible by the construction industry and appropriate policymakers. By introducing occupational safety management relating to the model of risk identification and safety management of the research area, the government could take the necessary initiatives for the prevention of accidents. This research will provide information about the hazard identification for critical incidents and the hazards that could lead to the uncontrolled critical risk events.

The research will add to the knowledge base of new safety risk assessment and management models in the construction domain in Thailand to improve workers' well-being and business functions. Moreover, this study can be used to help and guide the parties on construction sites to minimise the potential risks. Recommendations will be generated which can help industries to improve the safety management performance on building construction sites.

1.7 Organisation of the Thesis

The thesis comprises nine chapters followed by the references and appendices. The outline of these chapters is as follows:

Chapter 2 presents a review of the literature on construction projects in the building construction industry, and introduces the current practice of safety risk management in the construction industry. The concept of the risk assessments, Construction (Design and Management) Regulations 2015 and the fuzzy reasoning approach, AHP and TOPSIS are reviewed.

Chapter 3 discusses the methodologies that will be applied to achieve the aims and objectives of this research.

Chapter 4 provides an analysis of the feedback and the research findings. The analysis of the questionnaire surveys is discussed.

Chapter 5 outlines FRT, FAHP, MFAHP, and FTOPSIS.

Chapter 6 presents a construction safety risk assessment and management model developed by using FRT, MFAHP and FTOPSIS. The third safety risk assessment parameter, probability of consequence, is proposed. A case example is presented which demonstrates the effectiveness of the developed safety risk analysis model in construction safety risk management.

Chapter 7 outlines case studies collected from real construction projects by applying the proposed construction safety risk management model. The interview findings on how to manage high risks in the Thai building construction industry are provided. Risk responses for specific construction projects are discussed.

Chapter 8 presents the findings of the research. The achievements in the study, contribution of knowledge and impact of the study are discussed.

Finally, Chapter 9 presents the conclusions, recommendations and the limitations of using FRT, MFAHP and FTOPSIS in the building construction safety risk management process and discuss how the research aim and objectives are achieved. At the end, suggestions are made for future studies.

1.8 Summary

This chapter provided the background of the study, including the statement of the problems and the aims and objectives related to the development a new risk assessment and occupational safety management model in construction projects. The chapter started by discussing the importance of construction project safety on construction sites and their dangerous activities owing to the unique features of construction work, such as the different hazards and risks that continually emerge during daily jobs, and the changes in construction processes and procedures in different kinds of projects that may lead to safety risks faced by construction workers. Then, the increasing importance of risk assessment and management mechanisms for safety for construction industries was discussed. Moreover, the review of safety risk data and information in the construction industry showed that there is a high level of uncertainty in determining the safety risks. Challenges and problems which cause poor performance in coping with risk hazards in construction activities were also discussed.

The significance of the novelty of this research and the research outcomes were discussed, and the organisation of the thesis was outlined. The next chapter presents a review of the major statistics relating to construction accidents, safety risk assessment and management in building construction projects and the Construction (Design and Management) Regulations 2015 (CDM 2015). Specifically, the FRT, AHP and TOPSIS concepts are interpreted.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter provides details of the major statistics relating to construction accidents. The definitions of safety risk assessment and management related to building construction projects, construction safety risk management, construction (design and management) Regulations are outlined. Major injuries in building construction industry are reviewed. Finally, FRT, AHP and TOPSIS are discussed.

2.2 Safety Management in Construction Industry

2.2.1 Safety Management Framework

The safety management framework consists of a set of measures relating to safety management which are operated and implemented continually. Most of the key elements required for safety management are similar to those for construction management, business financial management, and total quality management. Hughes and Ferrett (2012) identified five key elements in a successful safety management framework, as shown in Figure 2-1.

2.2.1.1 Policy

Organisations should have a well-prepared documented policy regarding the ILO Guidelines on occupational safety and health management systems (ILO-OSH, 2001) provides general guidelines for a safety policy application as:

a) The policy should be suitable with scales and types of organisations.

b) It should be clearly and simply written and approved by the head of the organisation so that it can be simply applied by employees.

c) It should be circulated by different means of communication and followed by employees, who should be familiar with its instructions.

d) It should be editable for continuous updating.

e) It should be available for external auditing and for other related parties.

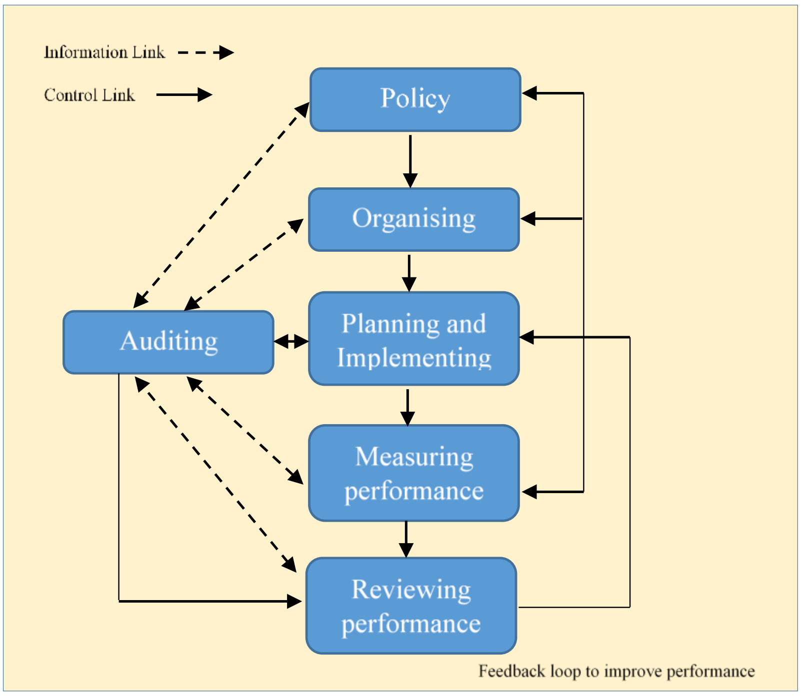


Figure 2-1: The principles of the safety management framework (reproduced from Hughes and Ferrett, 2012)

2.2.1.2 Organising

The organisation section of the policy should provide the names and duties of the people within the organisation who are responsible for the development of the policy and its communication to the workforce. Two key personnel to be identified are the most senior accountable person for managing occupational health and safety and the health and safety competent person (ILO-OSH, 2001; Hughes and Ferrett, 2012).

2.2.1.3 Planning and implementing

This section outlines the arrangements in place within the organisation for dealing with any specific hazards, for example, legal requirements, health and safety rules and procedures, and the provision of facilities. Risks arising from workplaces, hazardous substances, activities, and fire should be evaluated and managed (ILO-OSH, 2001; Hughes and Ferrett, 2012).

2.2.1.4 Measuring performance

This stage consists of the following: conducting an internal audit, evaluating legal compliance, identifying non-conformities, and actively monitoring people, procedures, and systems. The most effective and robust systems ensure that this process runs smoothly at all times. This means that the performance of this process should be measured as well, and any non-conformities must be dealt with (ILO-OSH, 2001; Hughes and Ferrett, 2012).

2.2.1.5 Reviewing and auditing performance

The best control systems deteriorate over time, or become obsolete due to changes or new processes. Therefore, it makes sense to review the policy periodically to ensure that it remains effective, measure the aims and objectives and update the organisational and arrangement sections as necessary (ILO-OSH, 2001; Hughes and Ferrett, 2012).

2.2.2 Occupational Health and Safety Assessment Series (OHSAS 18001)

The occupational health and safety assessment series (OHSAS 18001) is a widely recognised occupational health and safety management system which includes a process to identify, reduce, and control potential safety risks to prevent accidents and improve operational performance (Pheng et al., 2003; Omran et al., 2008; Marhani et al., 2013). It was developed to comply with the ISO 9001 (Quality) and ISO 14001 (Environment) management system standards to organise the combination of quality, environment and occupational health and safety management systems. The basis of the core elements of OHSAS 18001 is shown in Figure 2-2.

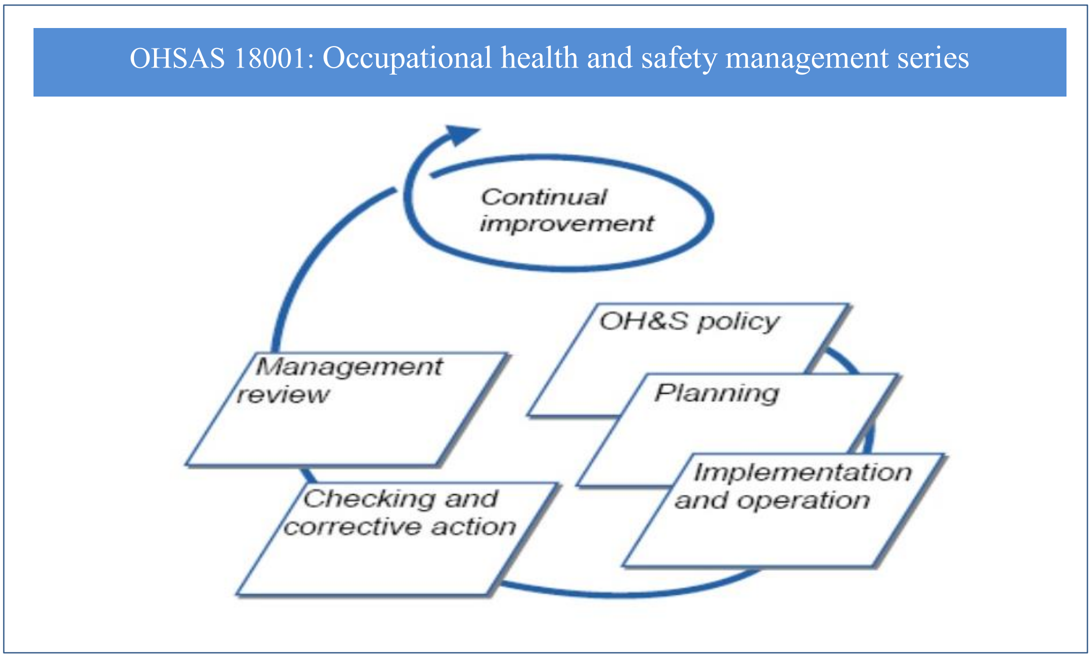


Figure 2-2 **:** Occupational health and safety management system model for OHSAS 18001 standard (reproduced from OHSAS, 2007)

2.2.2.1 Occupational health and safety

In this stage, the occupational health and safety (OH&S) policy should be established and authorised by the organisation's top management (OHSAS, 2007). A documented policy should be defined to ensure that it is appropriate to the nature and scale of the organisation's occupational health and safety risks, including a commitment to preventing injury and improving occupational health and safety continually (OHSAS, 2007). This policy provides the framework for setting and reviewing occupational health and safety objectives.

2.2.2.2 Planning

The planning stage of the process requires the organisation to establish, implement, and maintain procedures for (OHSAS, 2007):

Table 2-1: Planning requirements of OHSAS 18001

Heading	OH&S management system requirements
Hazard identification, risk assessment and determining controls	▪ Human factors and human behaviour and capabilities ▪ Non-routine and routine works of all personnel ▪ All workers' activities, including visitors and contractors ▪ Created hazard works related to all activities under the control of the organization ▪ Materials, infrastructure and equipment ▪ Changing activities or materials in the organization ▪ Alteration of the occupational health and safety management system, including the process, operation and changing activity ▪ Any applicable legal obligations related to risk assessment and implementation of necessary controls ▪ Work design, work organisation, processes, installations, machinery/equipment and operation procedures
Legal and other requirements	The organisation should identify relevant legal and other requirements
Objectives and programmes	The objectives should be measured and reviewed based on the legal and other requirements, and the programmes should be included with the designated activities of the organisation through the regular reviewing and planning

Furthermore, the organisation is responsible for establishing, implementing and maintaining the occupational health and safety management system in the organisation to ensure that the occupational health and safety risks and determined controls are taken into account.

2.2.2.3 Implement and operation

Emergency response procedures will be required to deal with potential incidents, accidents, and emergencies. A process will be needed for the occupational health and safety team to assess compliance with legal and other requirements. Monitoring and measuring of equipment will need to be controlled and calibrated. Records will be need to simplify preventive and corrective actions. Impact safety will be required for measuring and monitoring process and product characteristics.

2.2.2.4 Checking

Appropriate emergency preparedness operation procedures should be developed to identify, mitigate and prevent potential incidents and emergencies. A documentation procedure to control nonconformities must be identified, assessed, and controlled appropriately when specified process limits have exceeded potentially unsafe conditions. Moreover, corrective actions should be identified and eliminated to reduce safety risks and the nonconformities.

2.2.2.5 Management review

Internal audits, corrective actions, analysis of data, and updates of the occupational health and safety management system must be continually reviewed using management reviews to improve the occupational health and safety management system.

2.2.3 Construction (Design and Management) Regulations

The Construction (Design and Management) Regulations 2015 (CDM 2015) were updated in April 2015, replacing CDM 2007 (Patterson et al., 2015). These Regulations apply to all construction work within the UK, including workers, domestic clients, clients, principal contractors, contractors, principal designers, and designers (HSE, 2015). CDM 2015 is divided into five parts:

Part 1 deals with the application of the definitions CDM 2015.

Part 2 covers the duties of clients that apply to all construction projects.

Part 3 contains the health and safety duties and roles of other duty holders.

Part 4 includes the general requirements for all construction sites.

Part 5 contains transitional arrangements and revocations.

The key elements include managing the risks by applying the general principles of prevention, appointing the right people and organisations at the right time, and ensuring that everyone has the instruction, supervision , information, and training they need to carry out their jobs in a way that secures health and safety (Patterson et al., 2015). Duty holders communicate and cooperate with each other and coordinate their work and engage and consult with workers to develop and promote measures to secure health, safety and welfare effectively (HSE, 2015). The different duty holders are summarised in Table 2-2.

Table 2-2: Summary of roles and duties of CDM 2015 (HSE, 2015)

CDM duty holders	Main duties
Clients	Confirm competence of all duty holders and confirm appointments of duty holders for managing a project and notify the HSE of construction projects. The pre-construction information is prepared and provided to other duty holders. The principal contractor and principal designer carry out their duties and welfare facilities are provided.

Table 2-2: Summary of roles and duties of CDM 2015 (cont.)

CDM duty holders	Main duties
Domestic clients	Domestic clients are under the scope of CDM 2015, but their duties as a client are usually transferred to the contractor on a single contractor project or the principal contractor on a project involving more than one contractor. However, a domestic client can choose to have a written agreement with the principal designer to carry out the client duties.
Designers	Prepare or modify designs to eliminate, reduce or control foreseeable risks that may arise during construction and the maintenance and use of a building once it is built. Information is provided to other members of the project team to help them fulfil their duties.
Principal designers	Help the client to present a project brief and pre-construction information. Ensure cooperation and coordinate health and safety in the pre-construction phase of a project, which includes identifying, eliminating or controlling foreseeable risks and ensure that designers carry out their duties and provide relevant information to other duty holders. The relevant information is updated and provided to help the principal contractor with planning, managing, monitoring and coordinating health and safety in the construction phase.

Table 2-2: Summary of roles and duties of CDM 2015 (cont.)

CDM duty holders	Main duties
Principal contractors	Develop a construction phase health and safety plan. Plan the work properly. Communicate the hazards, risks and any precautions required. Provide information instruction, training and supervision. Control, manage and monitor all sites. Ensure that design works undertaken during the construction phase are specifically assessed regarding to health and safety. Prepare the health and safety file.
Contractors	Formulate a construction phase health and safety plan for every project irrespective of the size, duration, complexity or type of construction work. Manage and monitor construction work under their control so that it is carried out without risks to health and safety. In the case of projects involving more than one contractor, coordinate their activities with others in the project team. Specifically, comply with directions given to them by the principal contractor or the principal designer.
Workers	Must be consulted about matters which affect their health, safety and welfare, take care of their own health and safety and that of others who may be affected by their actions, report anything they see which is likely to endanger either their own or others' health and safety, and cooperate with their employer, fellow workers, contractors, and other duty holders.

2.3 Overview of Construction Safety Management

The manufacturing industry is essentially very different from the construction industry; therefore, it is difficult to use the same safety management techniques and systems in the construction industry (Rowlandson, 2004). A review of the literature on construction safety reveals that much research effort has been focused on the increase in fatal or non-fatal accidents on construction sites as one of the most dangerous places (Carr and Tah, 2001; Chi et al., 2005; Zeng et al., 2007; Fung et al., 2010; Nieto-Morote and Ruz- Vila, 2011; Sansakorn and An, 2015; Senouci et al., 2015). The studies reveal the status of construction safety in some countries, and it can be inferred that construction safety is a major global problem. For example, the Bureau of Labor Statistics in the US (Bureau of Labor Statistics, 2015) highlighted that the 937 fatal work injuries in the private construction industry in the US in 2015 represented the highest total since the 975 cases in 2008, as shown in Figure 2-3.

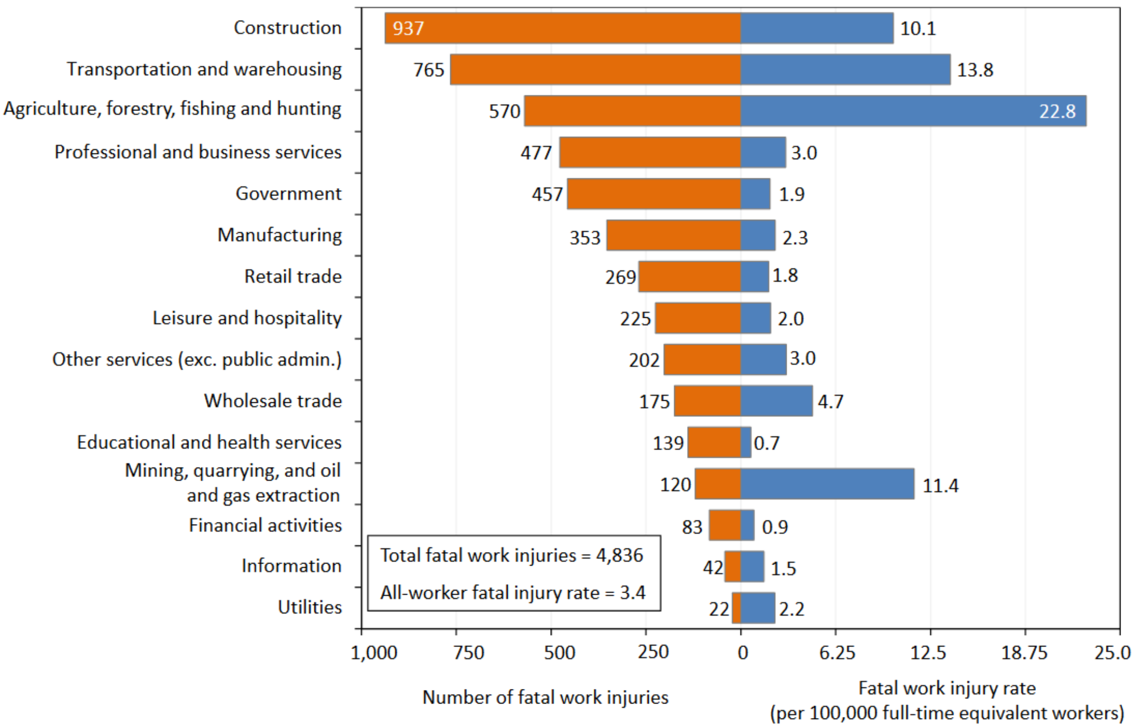


Figure 2-3: Number and rate of fatal work injuries in the US, 2015
(Source: Bureau of Labor Statistics, 2015)

According to Safe Work Australia (2015), which produces reports that provide information on the circumstances of work-related deaths in Australia, 30 fatalities were recorded in 2015 and the mechanism with the highest number of worker fatalities in the construction industry is falls from height. These fatalities accounted for almost one-third of the fatalities (133 out of 469 fatalities) in the industry.

Industry sub-division	Falls from a height	Vehicle collision	Contact with electricity	Being hit by moving objects	Being hit by falling objects	Being trapped between stationary and moving objects	Being trapped by moving machinery	Other	Total
Building construction	**34**	**9**	**5**	**2**	**15**	**3**	**1**	**5**	**74**
Non-residential building construction	10	5	1	1	7	2	1	1	28
Residential building construction	24	4	4	1	8	1	..	4	46
Construction services	**89**	**44**	**57**	**28**	**31**	**16**	**15**	**29**	**309**
Building completion services	26	2	3	3	4	3	1	1	43
Building installation services	15	12	38	1	..	1	..	5	72
Building structure services	35	6	12	4	7	4	2	6	76
Land development and site preparation services	5	12	1	15	15	8	11	10	77
Other construction services	8	12	3	5	5	..	1	7	41
Heavy and civil engineering construction	**10**	**20**	**5**	**25**	**8**	**4**	**3**	**11**	**86**
Construction total	**133**	**73**	**67**	**55**	**54**	**23**	**19**	**45**	**469**

Figure 2-4: Construction sub-divisions by mechanism of worker fatalities, 2003-2015 (Source: Safe Work Australia, 2015)

2.4 Background of Construction Safety Management in the UK and Thailand

2.4.1 UK Construction Industry Safety

The construction industry is one of the largest sectors for the UK economy. The importance of the UK construction industry to the nation's economy is clear to see. In 2014, the annual output of the construction industry contributed £103 billion in economic output, 6.5 per cent overall. The HSE in Great Britain (GB) recorded an accident rate of 0.55 per 100,000 workers in 2017, which was lower than that of many European Union (EU) member states, such as Sweden, Denmark, France, Germany, Italy, and Spain (HSE, 2017), as shown in Figure 2-5. Furthermore, the overall rate of fatal injuries at work in GB has consistently been one of the lowest across the EU (HSE, 2017).

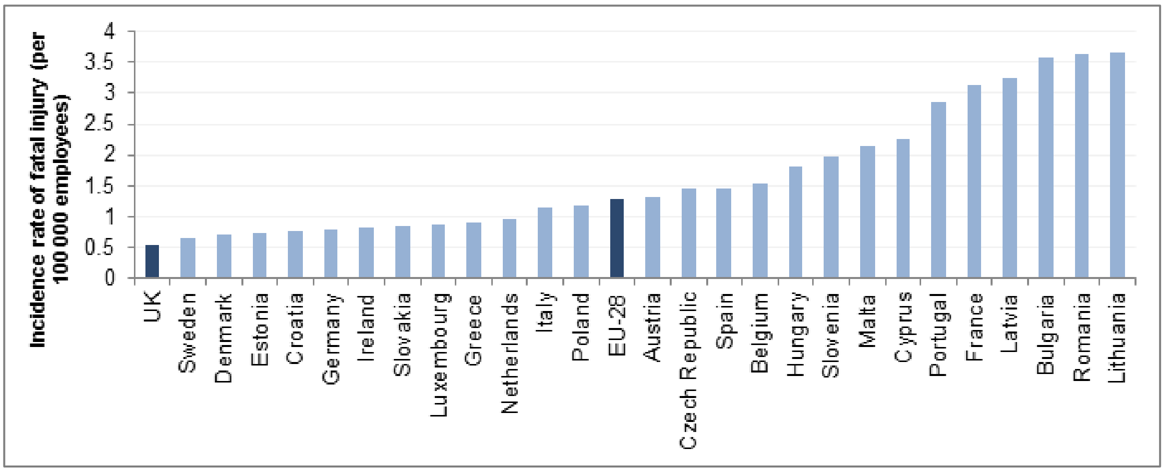


Figure 2-5: Rate of fatal injuries at work per 100,000 workers (Source: HSE, 2017)

Figure 2-6 presents the data on fatalities in GB construction per 100,000 workers. The overall trend of fatalities is downward. The number and rate of fatal injuries can vary quite significantly from year to year, and the rate of change is getting slower as the number of fatalities falls.

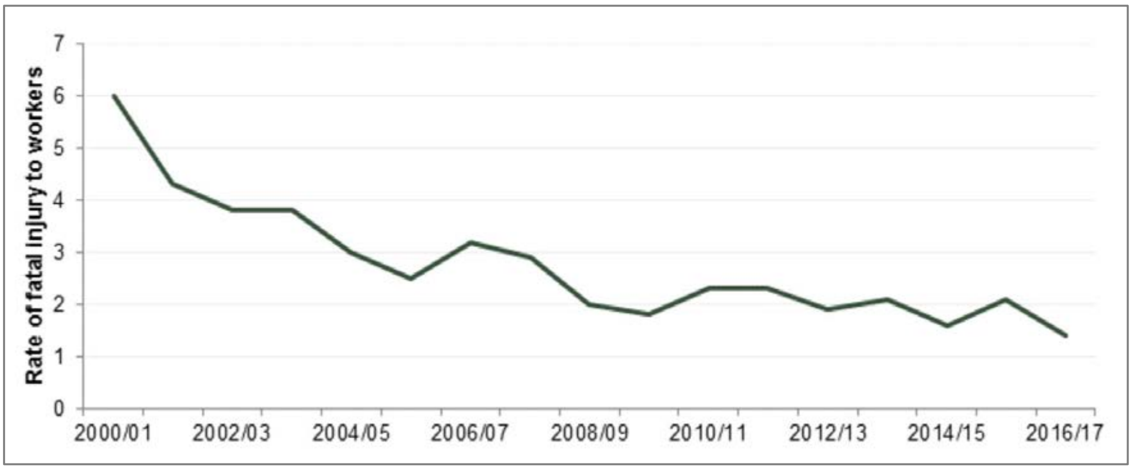


Figure 2-6: Number of fatal injuries to employees in construction, 2000-2017 (Source: HSE, 2017)

Figures 2-7 illustrates that the worker fatal injury rate in construction was 1.37 per 100,000 workers. This is more than three times the average rate across all industries. Furthermore, in 2016/17 there were 30 fatal accidents involving construction workers, around 30 per cent lower than the five-year average for 2011/2012-2015/2016 (HSE, 2017). Almost half of the fatal injury cases were caused by falls from height, as shown in Figure 2-8.

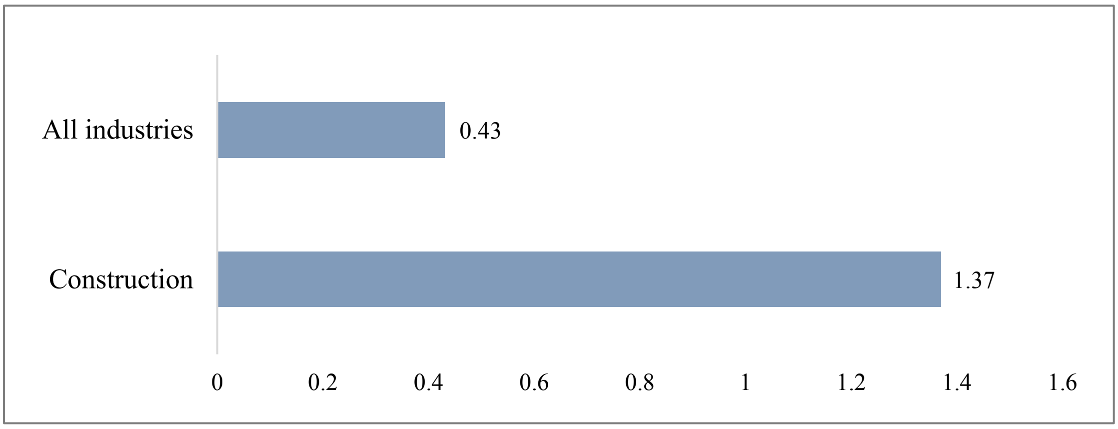


Figure 2-7: Rate of fatal injuries to employees in construction per 100,000 workers, 2016/2017 (HSE, 2017)

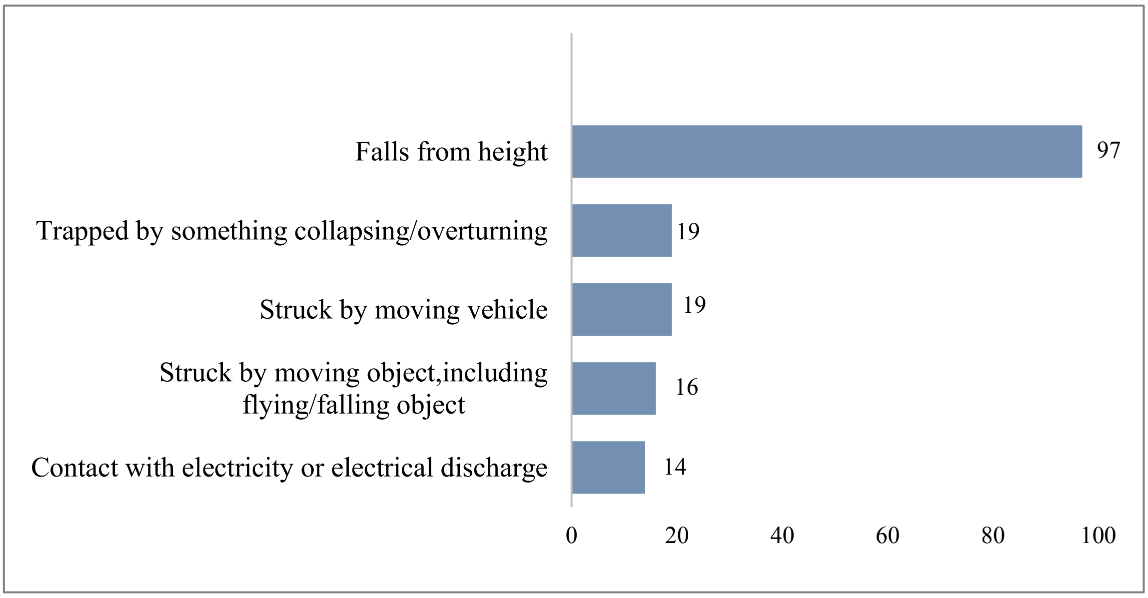


Figure 2-8: Main injury types for fatal injuries to workers in construction in the last five years (Source: HSE, 2017)

The most frequent causes of major injuries are presented in Figure 2-9.

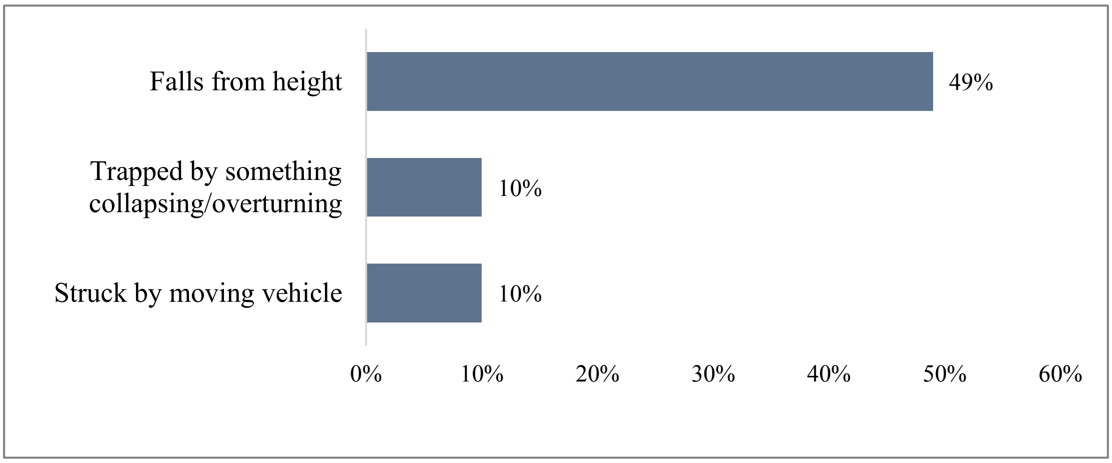


Figure 2-9: The most common causes of fatal injuries to employees, 2012/13-2016/17 (Source: HSE, 2017)

2.4.2 Thai Construction Industry Safety

Thai construction has been growing at a rapid rate. Data on both new construction and alterations collected by the National Statistical Office in 2016 shows that the total permitted number of workers in new building projects and alterations was 40,907 people, which comprised 35,842 people in building construction and 5,065 people in civil engineering construction. (National Statistical Office, 2016).

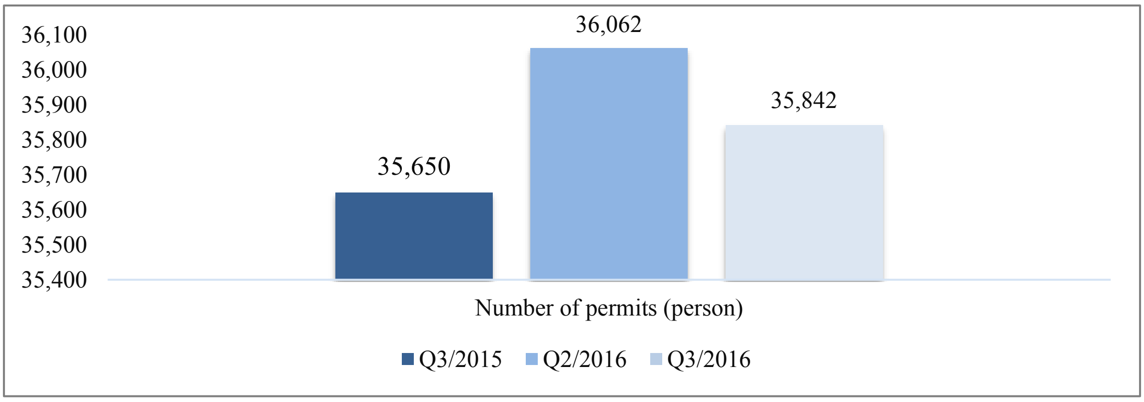


Figure 2-10: Number of permits for new building construction and alterations in Q3/2015, Q2/2016, and Q3/2016 (National Statistical Office, 2016)

The overall permitted construction floor area was about 10.4 million square metres in Q3/2016. Residential building accounted for about 65.1 per cent of the permitted floor areas, while hotel buildings accounted for 5 per cent. The floor area for education and health buildings was about 4.3 per cent, as shown in Figure 2-11 (National Statistical Office, 2016).

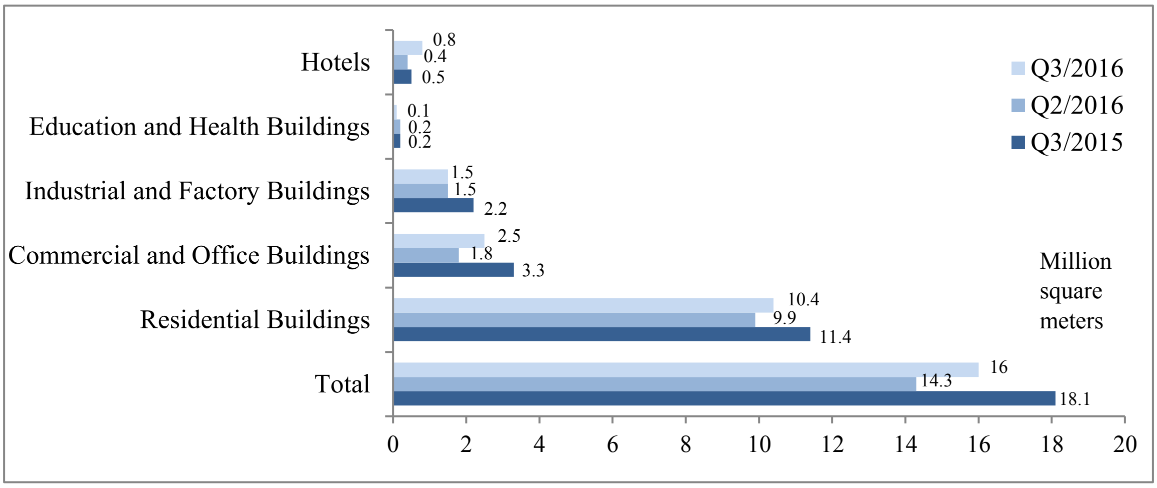


Figure 2-11: Permitted floor area of new building and alteration projects by type of building in Q3/2015, Q2/2016 and Q3/2016 (Source: National Statistical Office, 2016)

However, the number of construction accidents is decreased, as evidenced by the statistics on accidents in Thai construction shown in Figure 2-12.

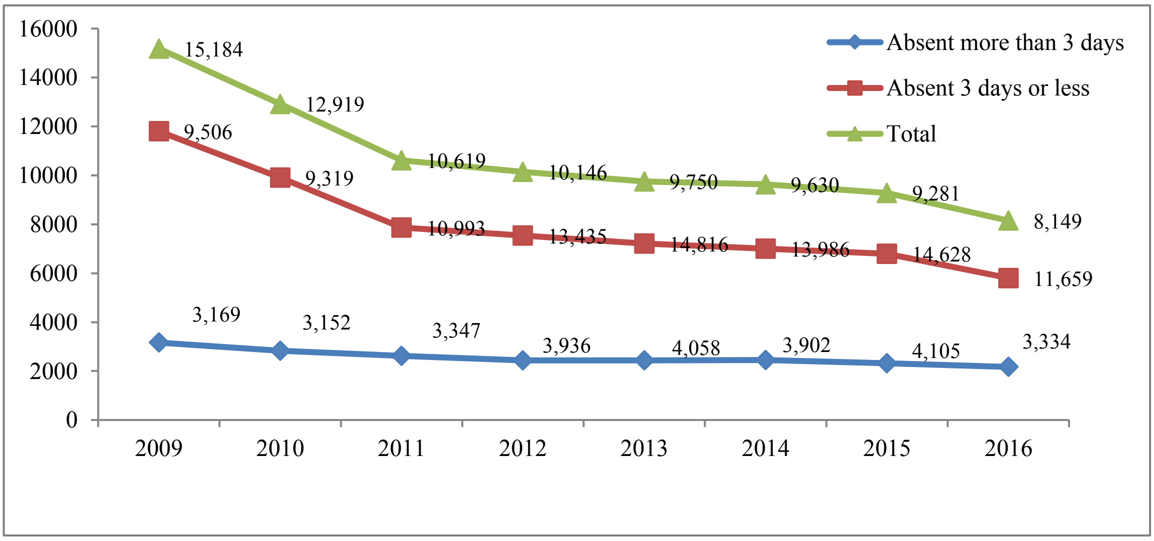


Figure 2-12: Major construction accidents in Thailand 2009-2016 (Source: Ministry of Labour and Social Welfare, 2016)

There are some major injuries in the building construction industry, which are outlined below as in Table 2-3 below. It includes the types of safety risks and the referenced articles for the final list of 15 safety risks extracted from literature.

Table 2-3: Major injuries in building construction industry

Type of safety risk	Sources	Discussion
Falls from height	Pipitsupaphol and Watanabe, (2000 cited in Hamid et al., 2008:247); Limsupreeyarat et al., (2010), Perlman et al., (2014), Grant and Hinze (2014)	Falls from height have been considered as one of the most frequent causes of death in building construction. It may occur due to unprotected openings in building or a lack of edge protection barriers, and it may be caused due to the ignorance and unawareness of workers
Falling objects	Pipitsupaphol and Watanabe, (2000 cited in Hamid et al., 2008:247); Leggat (2001)	The major causes of accidents associated with height are objects falling on workers or people below. In Thailand, statistics indicate that during the nine-month period from November 1997 to July 1998, three deaths and 11 injuries were a result of construction sites falls
Equipment, Machinery, Tools	Pipitsupaphol and Watanabe, (2000 cited in Hamid et al., 2008:247)	The main causes of construction injuries were due to improper loading or equipment placement or supplies; failure to warn co-workers or to secure equipment; and improper use of equipment. Construction sites in Thailand have poor safety measures
Collapse of site structure	Behm (2005), Rozenfeld et al., (2010), Gürcanli and Müngen (2013)	The brick wall collapsed onto the crane and crushed the worker as the brick wall was not designed to be freestanding
Manual handling	Kadikon and Rahman (2016), Laryea (2010), Gurcanli and Sevim., (2015)	The movement of loads by worker effort alone. It can include any activity causing overload of workers, such as lifting, pushing, pulling, and carrying

Table 2-3: Major injuries in building construction industry (cont.)

Type of safety risk	Sources	Discussion
Slips and Trips	Lipscomb et al., (2006), Fung et al., (2010), Dewlaney et al., (2011), Hu et al., (2011), Perlman et al., (2014)	Slips and trips are recognised as a serious source of injury in construction. Movement, speed of work jobs, and performance are related to injuries from slips and trips. Trips and Slips happen due to lack of awareness, poor attention to detail, absence of signage and markings, poor illumination, slippery surfaces, and access routes obstructed by materials
Electricity	Aneziris et al., (2012), Perlman et al., (2014)	Electricity is widely used in the building construction industry; however, there might be potential for hazards with possible fatal results. The cause was electrocution by contacted impermanent electricity panels
Traffic hazards	Cheng et al., (2010), Gürcanlı et al., (2015)	Working in close proximity to roads and trucks entering or reversing on construction sites
Vehicle overturn	Haslam et al., (2005), Aneziris et al., (2012)	Moving vehicle with loss of control. Crane overturn, mobile plant overturn, such as tractors, dumper trucks, forklifts
Fire and explosion	Aneziris et al., (2012), Vongpisal and Yodpijit (2014)	Fires caused by hot work are the most serious hazards for workers installing reinforcement. Working with or being near flammables/combustibles
Exposure to hazardous substances	Vongpisal and Yodpijit (2014)	Exposure to hazardous substances such as dust, vapour and solvent

Table 2-3: Major injuries in building construction industry (cont.)

Type of safety risk	Sources	Discussion
Radiation hazards	Arphorn et al., (2003), Vongpisal and Yodpijit (2014)	Safety signs have been used for radiation on construction sites to prevent exposure to arc welding or exposure to or generation of lasers
Confined spaces	Mitropoulos et al., (2005), Tangtinthai (2016)	Separating demolition activities on construction sites has been involved with confined spaces. Entering tunnels, hoppers, vats, tanks or pits to inspect or test, work or clean
Noise and Vibration	Awakul and Ogunlana (2002), Henry and Kato (2012)	Noise and vibration can result directly from construction
Ergonomic/human factors	Chan (2011), Rosen and Meston (2011), Attaianese (2014)	Human error is most unpredictable. Unsuitable safety training profiles for workers may emerge for exposure to human factor risks, for example, poor work posture or repetitive movement

2.5 Safety Risk Assessment and Management

2.5.1 Definition of Risk

In the construction industry, risk can be defined in relation to occupational accidents leading to fatal incidents. According to Nieto-Morote and Ruz-Vila (2011), risk is intrinsic in all project undertakings, as it can never be fully eliminated, although it can be effectively managed to mitigate the impacts on the achievement of the objective of the project. Other definitions of risk are available in the literature, for example, “the traditional view of risk is negative, representing loss, hazard, harm and adverse consequences” (Jannadi and Almishari, 2003; KarimiAzari et al., 2011; Tangtinthai, 2016) and “the underlying condition that can generate a possible risk event at some time forward from the point of decision-making” (Winch, 2010). Zeng et al, (2005) state that the impact of risk can be measured as the probability of a specific unwanted event and its unwanted consequences or loss:

$$RM = RL \times RS \qquad \text{Eq. 2-1}$$

where RM = Risk magnitude; RL = Risk likelihood; and RS = Risk severity

Risk management is becoming increasingly important for the construction industry as construction projects involve uncertainty and complexity (Aminbakhsh et al., 2013). In many circumstances, however, based on the general agreement in the literature, risk management uses the following four-phase process (Mills, 2001; Zeng et al, 2005; Zeng et al, 2007; Nieto-Morote and Ruz-Vila, 2011):

- Risk identification
- Risk assessment
- Risk response
- Risk monitoring and reviewing

Furthermore, Winch (2010) suggests that risk management can be divided into four phases: identifying and classifying the risk; assessing the risk; responding to the risk, and controlling the risk, as shown in Figure 2-13 below.

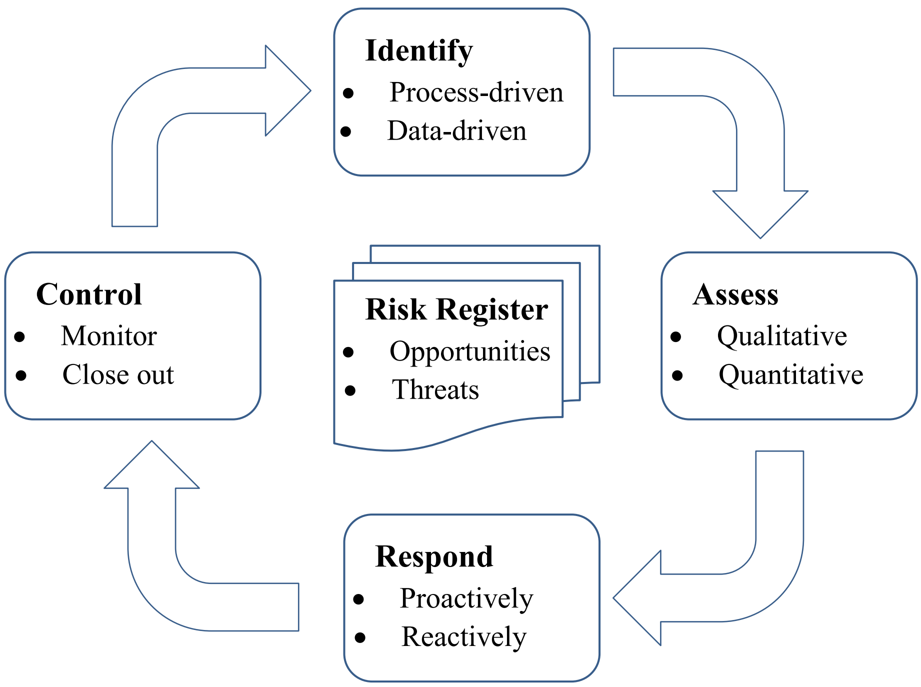


Figure 2-13: The risk management process (reproduced from Winch, 2010)

2.5.2 Risk Identification

KarimiAzari et al., (2011) and Zavadskas et al., (2010) highlight that risk identification is the essential first step in risk management. The identification of each risk is aimed at determining potential risks attached to assignments to be performed by workers. Identifying the source of risk and the components allows the risk item to be separated from others. An et al., (2011) suggest that the purpose of risk identification is to identify all potential hazardous events systematically. Moreover, various hazard identification techniques, such as the brainstorming approach, check-list, 'what if?' analysis, a hazard and operability (HAZOP study), FTA, and

FMEA, have been used (Zeng et al, 2005; Zeng et al, 2007; An et al., 2011; Pinto et al., 2011;).

2.5.3 Risk Assessment

Risk is assessed from the risk identification in the previous stage. Some authors refer to the processes which include identifying and assessing risks, as the stage called 'risk analysis'. The main purpose of risk assessment is to assess the risk by identifying potential undesirable events, the probability of occurrence of the events, and the consequences of such events (Gürcanli and Müngen, 2009; KarimiAzari et al., 2011). The risk likelihood and risk severity that can be caused by a hazard are considered. Zeng et al., (2005) state that the risk criteria which are widely used in judging risk magnitude are risk likelihood, risk severity, risk timing, and risk impact. Risk likelihood and risk severity are frequently used as fundamental criteria for risk assessment. Moreover, risk likelihood depends highly on personal experience and historical data obtained from company documentation and industrial records. Risk severity is the degree of seriousness and the scale of the impact if the risk turns into reality (Zeng et al., 2005). However, risk assessment methods have ranged from simple classical methods to fuzzy reasoning approach mathematical models, and a risk assessment model based on fuzzy reasoning and the AHP approach is proposed (Zeng et al., 2007).

2.5.4 Risk Evaluation

The main purpose of risk evaluation is to determine whether a risk is acceptable. If the risk is regarded as an acceptable risk as indicated in Figure 2-14, it may be sufficient to control the risk instead of reducing it. Conversely, if the risk is regarded as an unacceptable risk, measures must be taken to eliminate or reduce the risk (Zeng et al., 2005).

The results generated from the risk assessment stage may be used in the risk evaluation stage to help project managers, risk analysts and engineers to develop maintenance and operation policies (An et al., 2011). If risks are high, risk mitigation programmes must be applied to reduce the probability of occurrence or control the possible consequences. The unacceptable and acceptable regions are usually divided by a transition region, however.

Risk Severity	Very low	*Negligible*	*Negligible*	*Negligible*	*Tolerable*	*Tolerable*
	Low	*Negligible*	*Negligible*	*Tolerable*	*Tolerable*	*Tolerable*
	Medium	*Negligible*	*Tolerable*	*Tolerable*	*Tolerable*	*Intolerable*
	High	*Negligible*	*Tolerable*	*Tolerable*	*Intolerable*	*Intolerable*
	Very high	*Negligible*	*Tolerable*	*Intolerable*	*Intolerable*	*Intolerable*
		Very low	Low	Medium	High	Very high
		Risk Likelihood				

Description	General Interpretation
Negligible	The risk is low or insignificant and can be readily controlled.
Tolerable	The risk is medium and is tolerable in order to secure certain benefits. However, risk controls should be undertaken if it is reasonably practicable to do so.
Intolerable	The risk is unacceptable no matter what benefits associated with that risk. Proper action must be taken to eliminate or reduce the risk.

Figure 2-14: The matrix for risk assessment (reproduced from Zeng et al., 2005)

2.5.5 Risk Monitoring

The final stage in the risk assessment is the process of monitoring the identified risks. The control of the risk may involve choosing alternative strategies to ensure the execution of the risk plans and evaluate their effectiveness in reducing risk. Many hazards have had specific regulations and actions, or other recognised standards have been developed to mitigate the risks involved (Hughes and Ferrett, 2012). Moreover, when conditions change, a further review may be necessary due to the implementation of new machinery or processes or the development of new hazards (Hughes and Ferrett, 2012). However, when assessing the adequacy of existing controls or introducing new controls, a hierarchy of risk controls should be applied. The hierarchy of controls for risk consists of five stages (Cooper, 2001), as shown in Figure 2-15.

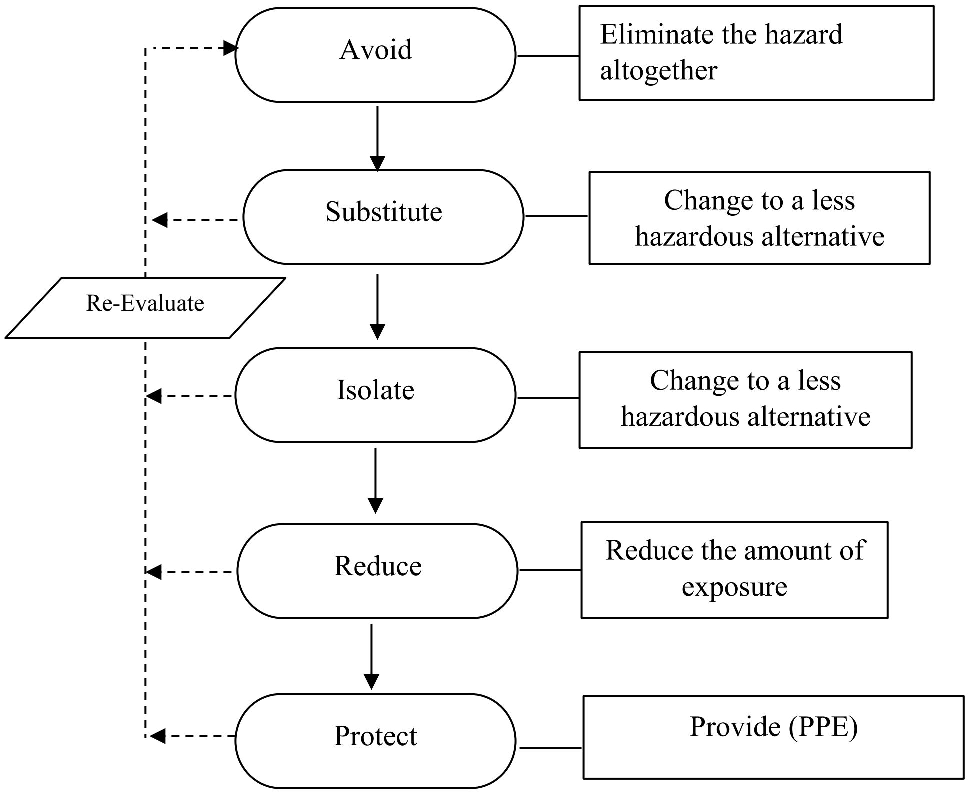


Figure 2-15: The hierarchy of control for risks (reproduced from Cooper, 2001)

2.6 Current Qualitative and Quantitative Risk Assessment in Construction Industry

Once safety risks are identified, their characteristics need to be evaluated to determine whether the safety risks require further control. Many different mature risk assessment techniques are currently employed in the construction industry based on safety risk probability and safety consequence (An et al., 2011; Pinto et al., 2011; Liu and Tsai., 2012;

Cagliano et al., 2015). Several safety risk assessment techniques, ETA, FTA, a HAZOP study, FMEA, and MCS, which are found in the literature that are outlined in the following section.

A HAZOP study is a systemic qualitative risk assessment technique which was originally applied in the chemical industry in the UK during the 1960s (Nolan, 2014). This method aims to detect and evaluate design faults, potential hazards, and operational problems in term of plant design and human error. It is principally useful for assessing possible hazards designed in a work process (Dunjo et al., 2010; Rossing et al., 2010). The HAZOP study is commonly based on the principle with several experts' backgrounds that they can identify more problems and interact when working together than when working separately and combining their obtained results. This technique is usually used to check safety design and running safety structures, improve the safety of existing facilities, and evaluate unwanted hazards designed, undesirable events in a system or a process. The process of this technique is divided into functional blocks. Guidewords are systematically formulated to determine how deviation from the intended operating conditions can lead to hazardous problems. However, HAZOP method is a complicated process of analysis and it is not suitable in construction project involved massive uncertainties and subjectivities (Zhang et al., 2014). An example of the HAZOP technique is shown in Figure 2-16.

FTA is a quantitative top-down risk assessment technique which was first introduced by H.A. Watson of Bell Laboratories in 1961. It is one of the most used widely techniques and has generated numerous studies in multidisciplinary fields such as safety management, quality management, security management, nuclear engineering, and human engineering (Hyun et al., 2015). It is a logical structure relationship between events and causes lead to failure, which is used to evaluate the probability of failure or reliability of complex systems. There are two basic types of FTA diagram notations: logic gates, such as OR gate and AND gate and the basic failure event is usually denoted with a circle. (Abdelgawad and Fayek, 2010; Zio, 2013). However, the construction of the tree in this method depends on the ability of the analyst who must be well experienced and trained, and this technique is not suitable in the risk analysis process under incomplete and uncertain situation (An et al., 2011; Zhang et al., 2014). An example of the FTA technique is shown in Figure 2-17.

HAZOP GUIDE WORDS

Parameter	Guideword	Deviation
FLOW	None, Less, More, Reverse Other, Also	No flow, Less flow, More flow, Reverse flow, Other flow, Contamination
PRESSURE	More Less	More pressure Less pressure
TEMPERATURE	More Less	Higher temperature Lower temperature

Ref.	Deviation	Cause	Consequence	Safeguards	Action	On
1	No flow	Wrong initiating sequence used by the customer	Delay. Possible damage from wrong sequence. Sale may be lost.	Required sequence is usual for the UK and uses illuminated buttons on the pump panel. The site operator can select and speak to each station.	A1: Consider installing an alert to the operator whenever delay between removing hose and start of pumping exceeds selected time (say 20 s).	PM
2	No flow	Supply tank at low cutoff level	Delay and frustration for customer as cause not apparent.	Alarm to site operator of impending loss of supply. Operating procedure to cone off pumps with prepared signage.	A2: Review restocking arrangements against the expected demands to minimize this situation.	SM
					A3: Review operator training and testing.	HS

Figure 2-16: An example of the HAZOP (reproduced from Crawley, 2015)

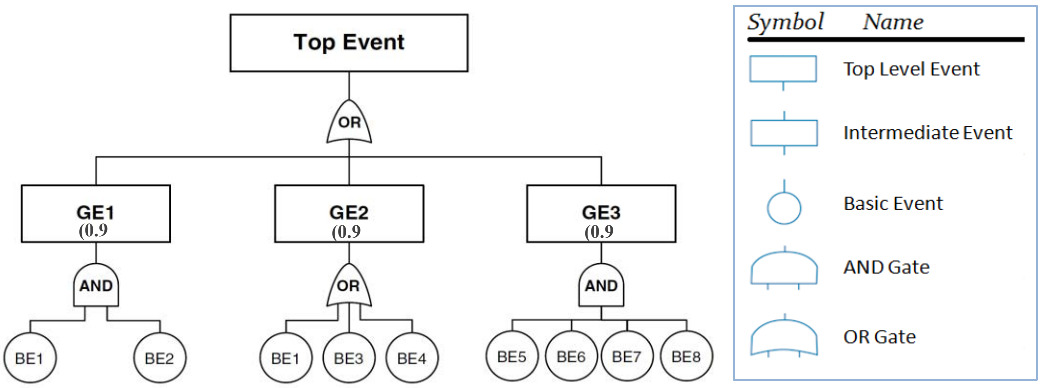


Figure 2-17 An example of the FTA structure

(reproduced from Abdelgawad and Fayek, 2010)

ETA is a quantitative bottom-up risk assessment technique which provides an analysis method for identifying and assessing the potential accident sequences involved in a specific initiating event (Zio, 2013; Ouache and Ali, 2014). This method is similar to the FTA method. It utilises a visual logic tree structure known as an event tree between the failures of defined safety functions and potential successes. An example of the ETA technique is shown in Figure 2-18.

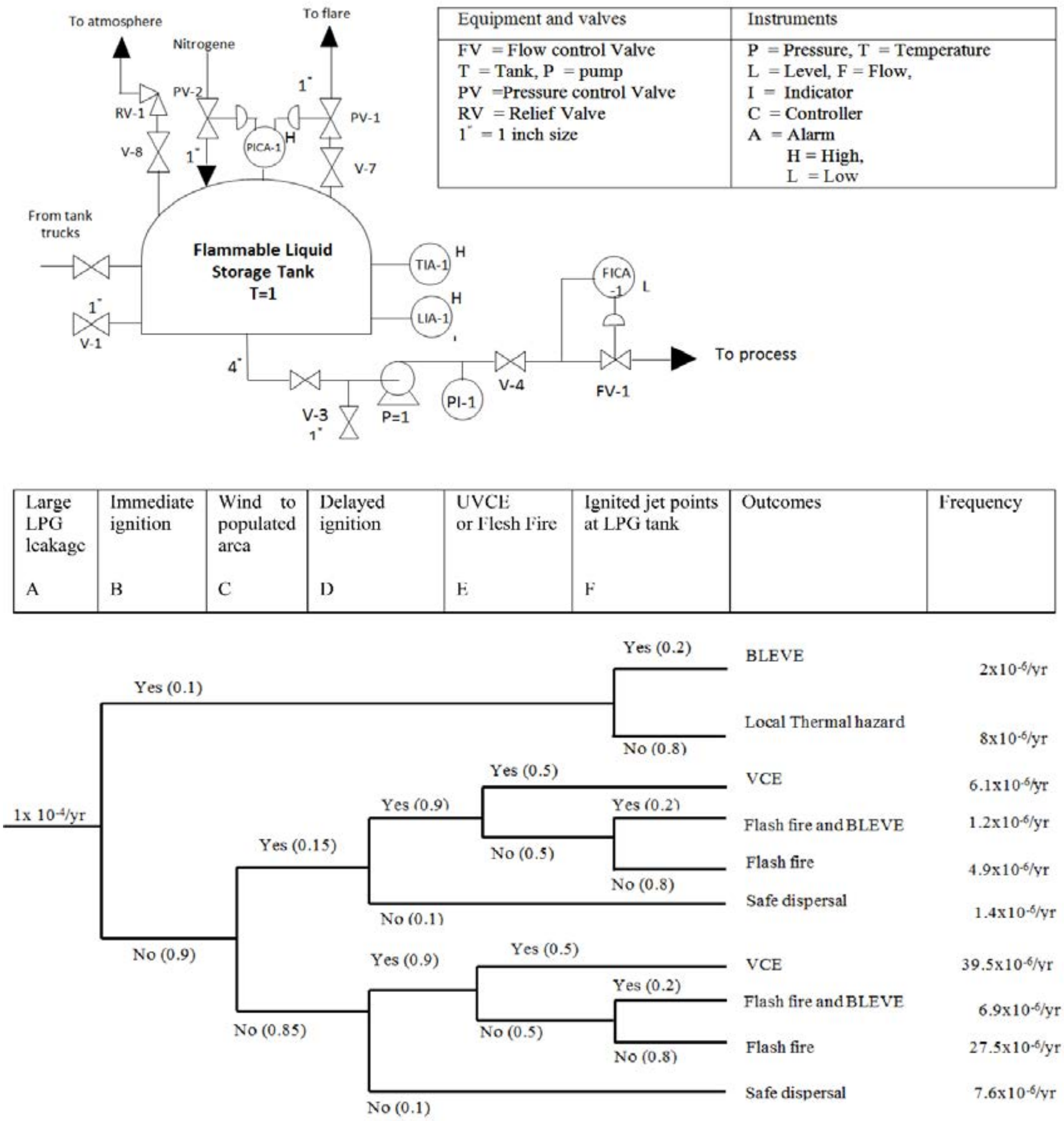


Figure 2-18 An example of the ETA (reproduced from Ouache and Ali, 2014)

FMEA is a quantitative bottom-up risk assessment technique that was first introduced by the National Aeronautics and Space Administration (NASA) in 1963 (Bahrami, et al., 2012) which can be employed to evaluate the effects of the potential failure modes of functions, components, and subsystem (Zeng et al., 2010). The concept of this technique is to calculate the risk priority number for each failure mode. FMEA states with a known potential failure mode at one level and then examines the effect on the next subsystem level (Sharma, et al., 2005). An example of the FMEA technique is shown in Figure 2-19.

However, ETA and FMEA are not suitable for risk assessment modelling under poor quality data and uncertainties (An et al., 2011; Yingying et al., 2016).

Failure Type: Collapse one part or total of excavation

The effect of potential failure	Severity S	Potential causes	Occurrence O	control	Detection D	RPN
Vertical displacement	8	There is over load(stress) near the pit (there is a hotel or a house)	9	Perform excavation step by step and depth of each step of excavation is 1 to 3 meters	7	504
Horizontal displacement	9	The soil is weak (the cohesion and internal friction is low)	10	Using SPT or CPT test to determining type of the soil	9	810
Cracks in the wall of neighbouring building	7	There are weak layers and lenses in loose soil	8	Use the kind of machine with low vibration in sensitive soil	5	280
Subsidence in the neighbouring building	6	rise the Underground water cause of shower or any reason	6	Estimate amount of the rain in the region according to the season , locate underground water level (if needed, control the water level by the mentioned methods)	9	324
Collapse total wall excavation due to collapse partial of wall excavation	10	The weak earthquakes or strong vibration	8	Stabilization the wall excavation with nailing or anchorage systems	10	800
rubble remain of Workers due to falling pit	9	Create dynamic motion around the excavation (due to vibration drilling)	4	Use shotcrete method and other temporary stabilization ways	6	216

Figure 2-19 An example of the FMEA (reproduced from Bahrami, et al., 2012)

Monte Carlo simulation (MCS) is one of the powerful modelling tools for analysing and evaluating complex systems in project risk analysis (Rezaie et al., 2007; Kwak and Ingall., 2007; Zio, 2013). MCS was named after the city in Monaco which is known for games of chance, for example, roulette wheels, with involve repetitive events with known probabilities. This method has also been useful in domains outside project management, such as engineering, computer applications, finance, and public health. It has been widely used in risk assessment based on a combination of multiple probability density functions in risk to quantify uncertainty in a probabilistic framework using computer simulation (Arunraj et al., 2013). However, MCS is not suitable for construction risk management, as the information arising contains subjective and linguistically expressed information (Sadeghi et al., 2010).

2.7 Review of FRT, AHP and TOPSIS

The FRT, which was first introduced by Zadeh in 1979 provides a useful mathematical process for reasoning to cope with uncertain and imprecise information. Taylan et al., (2014) state that construction projects are complex, are exposed to high degrees of risk, and face a significant amount of uncertainty. It is difficult to assess the risk level. Therefore, using the fuzzy expert system based on risk analysis can accommodate experts' experience and judgement and can prove helpful for contractors when conducting project risk management.

An et al., (2011) studied the FRT to assess the railway risk in the UK railway industry qualitatively. They state that fuzzy reasoning approaches are knowledge-based and constructed from expert knowledge in the form of if-then rules, which can provide a systematic procedure for transforming a knowledge base into non-liner mapping. Furthermore, Zeng et al., (2007); Nieto-Morote and Ruz-Vila (2011) state that using the FRT method has advantages which mean that it can be used to assess risks associated with construction projects effectively in ambiguous situations based on substantial uncertainties and subjective judgements.

Furthermore, Majumder et al., (2013) argue that the FRT is a key solution for dealing with uncertain, incomplete, ambiguous, and imprecise information in the historical data (the percentage of accidents, severity of accidents, and safety expenditure and activities), which can help safety professionals and engineers to improve the safety management system of the construction sites. Moreover, Lam et al., (2001) state "The fuzzy reasoning involved the transformation of linguistic variables into quantitative variables, and the exploration of the meanings of linguistic variables for the assignment of fuzzy sets to linguistic variables is essential for the resolution of fuzziness, vagueness, uncertainty and imprecision in decision-making problems". Therefore, the FRT should be considered as an effective tool to solve problems where there is complexity or imprecision. It enables the handling of imprecise information and uncertain knowledge in the construction industry, which can utilise a fuzzy rule-based system to describe nonlinear functions linguistically.

The AHP, developed by Thomas Saaty in 1980, is a quantitative technique based on mathematics to solve many complicated decision-making problems using a hierarchical structure (Taylan et al., 2014). Nowadays, it is widely used around the world to solve multi-criteria decision-making (MCDM) problems in domains such as business, industry, and health and safety, which helps in setting their priorities (Badri et al., 2012; Aminbakhsh et al., 2013). The AHP has also been used for identifying and weighting in the field of project risk assessment (Zeng et al., 2007, An et al., 2011; Nieto-Morote and Ruz-Vila, 2011). This structured technique works by minimising complex evaluation criteria into a series of one-to-one pairwise comparisons (Taylan et al., 2014).

To obtain the factor contributions of the evaluation criteria, Liu et al. (2015) employed the AHP to obtain the subjective weights of each risk factor by pairwise comparisons. Consequently, the risk factor weights were determined, which made the risk analysis results more consistent with the actual situation.

Aminbakhsh et al., (2013) adopted the AHP for prioritisation of safety risks in a construction project with the theory of cost of safety. The proposed safety risk framework revealed that the AHP can provide a robust method for creating a rational budget for accident prevention during planning and budgeting of construction projects. Moreover, Gudienė et al., (2014) applied the AHP to rank different critical success factors for construction projects in Lithuania. Based on their findings, the weight of the critical success factors by using the AHP can rank different construction projects successfully.

Furthermore, Li et al., (2013) employed the FAHP method in a case project for modular construction in Canada within a framework aimed to identify risk factors and assess the impacts of the identified risk factors on project costs and duration. This method is utilised to determine the weightings of risk factors in construction projects.

Another area in which fuzzy logic has been widely used is in decision-making processes. For instance, the TOPSIS technique was originally suggested in 1981 by Yoon and Hwang for solving MCDM problems (Yoon and Hwang, 1980; KarimiAzari et al., 2011; Tamosaitiene et al., 2013; Jato-Espino et al., 2014). This technique is a very helpful concept for coping with situations which are too complex to be calculated (Zavadskas et al., 2010). The main idea of this technique is that an alternative is chosen that should have the shortest and the farthest distances from the positive and negative ideal solutions respectively (Tan et al., 2010). However, the traditional formulation of the TOPSIS method, based on human judgements in the decision-making process, is represented with crisp numbers, non-obtainable and incomplete information. The FTOPSIS method will be discussed in Chapter 5.

Torfi et al., (2010) applied FAHP to obtain the criteria weight factors and applied the FTOPSIS method for evaluating the alternative rankings when the criteria weights and performance ratings were vague and inaccurate. They indicate that in combination, these are practicable techniques for coping with the performance ratings and the challenges of vague and imprecise information.

Taylan et al., (2015) carried out risk assessment of a selection of construction projects based on imprecise, ambiguous and uncertain information by using FAHP to obtain appropriate weights for five main criteria and then applied FTOPSIS to rank 30 construction projects in Saudi Arabia.

Haghshenas et al., (2016) applied FTOPSIS, which is a powerful and effective tool to rank risk, for solving complex problems under implicit conditions and with uncertain information in risk assessment of dam construction projects. Similarly, Tamošaitienė et al., (2013) studied the risk assessment of construction objects for a commercial centre construction project under a fuzzy environment, in which FTOPSIS was applied for risk assessment to rank three commercial objects.

Mousavi et al., (2015) proposed an MCDM model by employing the FTOPSIS method to rank appropriate construction projects under an intuitionistic fuzzy set environment. The ranking results compared with FTOPSIS were efficiently applicable for determining the criteria's weights to obtain a precise solution. Moreover, Junior et al., (2014) suggest that although the application of both FTOPSIS and FAHP is suitable to solve the supplier selection problem, FTOPSIS is better suited to solve the problem of supplier selection.

2.8 Summary

This chapter has reviewed the literature on safety management in the construction industry. The statistics on the previous accidents and incident reports in some countries differ from those in other countries, as health and safety systems in other countries differ regarding recording, reporting, and enforcement. Therefore, the background of construction safety management in the UK and Thailand has been focused on this chapter. According to the data on constriction fatalities the UK, it had the lowest fatal accident at work rate of all EU countries. One of the most significant issues in this chapter is that the construction industry has a higher risk level than other industries. This chapter also reviewed the concepts of the safety management framework and OHSAS 18001. This review revealed that the main features of the safety management framework and OHSAS 18001 are occupational health and safety management systems, which are a fundamental part of their safety risk management strategy to deal with the potential safety risks in the building construction industry. Moreover, many of the general risk assessment techniques in the construction industry use two fundamental risk parameters, risk likelihood and risk severity, to assess the risk level. Many of the construction safety risk assessment models may be unable to determine the safety risk level, however. For example, a specific risk depends highly upon the probability that the accident will occur, as these two parameters do not take into account the probability of the consequences caused in the construction projects.

It was found that many of risk assessment techniques are widely used in risk assessment, for example, FMEA, ETA, HAZOP, FTA, and MSC have limitations. They do not deal well with uncertainty and imprecise and ambiguous information. Furthermore, quantitative risk data are not always available when needed or not in the form required, therefore using subjective judgements are often more appropriate for safety risk assessment. The subjective approach or human judgement mainly utilises the relation measures of expert experience and knowledge.

This chapter also discussed the FRT, AHP and TOPSIS methods and found that the FRT method would be used in the risk criteria calculation and estimation stages in the construction safety risk management model to assess the potential safety risks and reduce the uncertainties, subjectivity, ill-defined problems, and vague information associated with building construction projects and activities.

It was found that FAHP has the advantage of reducing the number of pairwise comparisons, especially when there are a huge number of comparisons, which would be employed in the risk ranking stage to obtain the weighting factors that will be used in the FTOPSIS process. Furthermore, FTOPSIS would be used to rank the important safety risks under a vague and fuzzy environment.

In conclusion, this chapter discussed the safety management systems and safety risk management process, and reviewed the major safety risks in the construction industry. Therefore, it is expected that the proposed model that will be developed can be applied under a vague and fuzzy environment in construction projects and various other areas.

The next chapter, Research Methodology, outlines the methodology adopted in the thesis, including the research design, questionnaire survey design and model testing design. The case study and robustness and limitations of the approaches are also outlined.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Introduction

In this chapter, the research methodology is described, highlighting the importance of the key steps in the research and describing the methods to be used to develop a construction safety risk management model based on FRT, MFAHP and FTOPSIS. A questionnaire is employed as a survey programme to collect data on the building construction sites. The next steps in this research, the development of the research model, model testing, case studies and group interviews, are described. The chapter ends with the limitations and robustness of the approaches relating to develop a construction safety risk management model.

3.2 Research Design

The research design should be the most appropriate to obtain an answer to the proposed research questions. It is selected by considering how to connect the research with the data and information and the analysis of the results. According to Lyons and Skitmore (2004), common data collection methods are frequently used in the qualitative research method. Meng (2012) states that using a mix of qualitative and quantitative methods is more useful and makes the research more reliable. Therefore, combined qualitative and quantitative methods have been adopted in this research to confirm the identified safety risks and find other important safety risks on the building construction sites, and interviews will help to determine how to manage the safety risk. The following section will discuss each stage of the research design. Figure 3-1 shows the research design of the study.

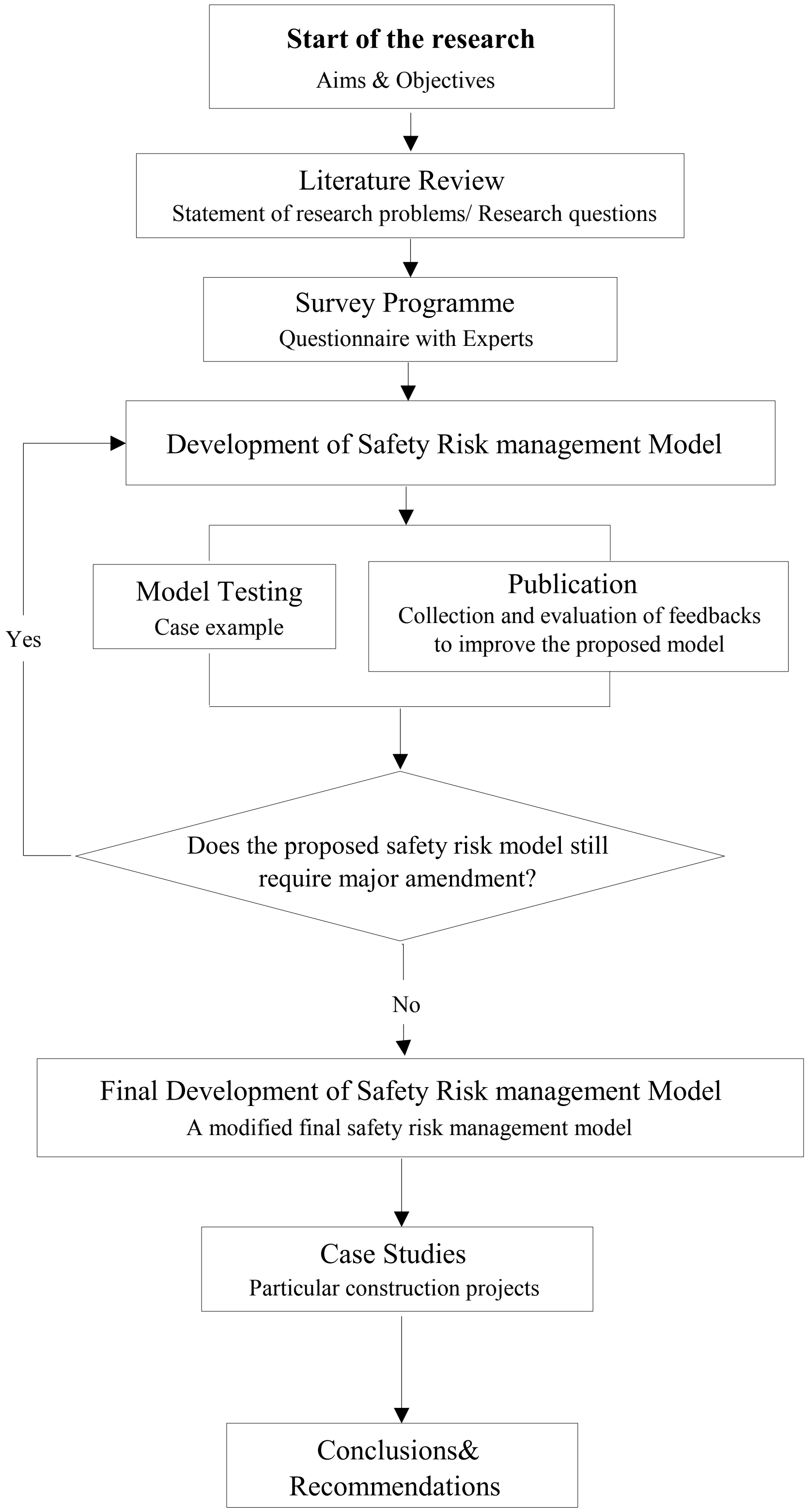


Figure 3-1: The research design of the study

3.2.1 Research Objectives

As stated earlier, the overall aim of this research is to provide an effective tool to develop safety risk management measures based on the development of a mathematical approach to building construction projects. The objectives of the research are achieved with the help of the FRT, AHP and TOPSIS methods, which will help the safety risk management terms to reduce injuries and improve the safety of workers within the building construction industry.

3.2.2 Problem Identification and Literature Review

Stage two of the research design will examine the current occupational safety problems, and the various types of safety risk in the Thai building construction industry will be investigated. Data and information on accidents in the building construction industry will be collected from reports, articles and the industry, and will draw on the source of possible safety risk in formulating the theoretical and research framework identified through the literature review. Many hazard identification techniques are currently used, for example, brainstorming, checklist, 'what if?' analysis, and a HAZOP study (Zeng et al., 2007). Specifically, this study will seek to address how safety risks are assessed in the Thai building construction industry. The review of the literature has found other research studies that supported this research work on the construction safety risk assessment and management domain during the whole research project, which is described in Section 2.7. An essential early stage of this research is examined potentially relevant theories and literature. Furthermore, the concepts of FRT, AHP and TOPSIS were reviewed.

3.2.3 Survey Programme

A questionnaire survey is a tool for data collection (Lyons and Skitmore, 2004) in which respondents are asked to give written or verbal replies to a written set of questions. A cover letter will be attached to the questionnaire explaining the aim and objectives of the research study and guaranteeing the confidentiality of the responses. In this research, the questionnaire survey will be used to collect and confirm identified safety risks based on the knowledge obtained from the literature review and to find other important risks in the Thai building construction industry. Based on the survey programme, an ethical review of the research is required and an application to obtain permission/information is required. Respondents will be informed that they can withdraw from the research at any time and that the data will be anonymised once it has been collected. All data will be kept in a locked cabinet and the computer used will be password protected.

3.2.4 Development of Research Model

The conceptual model for the study will be based on problem-solving in mathematics. The information obtained from the review of various methods of estimating safety risks on construction projects and from the data collection will be utilised to define the standards of qualitative descriptors and the associated safety risk management model. Secondary sources will be interpreted and processed for the analysis of the safety risk management model. The proposed model will address quantitative risk data and documentation generated by industries which are generally insufficient for determining the safety risks. Three parameters, probability of occurrence (PC), severity of consequence (SC), and probability of consequence (PC) will be incorporated into the proposed model. The FRT, MFAHP and FTOPSIS methods will be combined to develop a new safety risk management model, which will be used to obtain the final ranking to evaluate important safety risks in the construction projects.

3.2.5 Model Testing

In this stage, the proposed model will be tested by using a case example to ensure successful model development to generate results efficiently and effectively. The proposed construction safety risk management model testing will have two possible results: satisfactory or unsatisfactory. If the result is not good enough to be accepted, then the existing data will need to be verified or the model will need to be modified. Furthermore, a conference paper will be published to communicate, interact and negotiate with the international audience working in the same field, which will generate useful feedback on the proposed model.

3.2.6 Case Studies

Case studies will help to identify the circumstances and are used as a tool to facilitate learning regarding specific projects (Yin, 2011; Yildiz et al., 2014). In this research, case studies are employed to verify the reliability of the risk assessment and occupational safety management model in the construction industry. The cases will be selected in Bangkok, Thailand. There has been a significant increase in the growth of building construction activities and occupational safety risk in the construction industry.

3.2.7 Group Interviews

Once the case studies have been collected from the specific construction projects, group interviews will be conducted with experienced building construction managers, safety managers, and senior engineers, who will provide their views on critical safety risk management on the building construction sites. Questions will be formulated to determine how to manipulate the critical safety risks. Many studies confirm that interviews are particularly useful for obtaining respondents' experiences (Turner, 2010; Brinkmann, 2014). All the group interviews will be conducted by the researcher himself. A face-to-face group interview allows the researcher to observe any non-verbal communication.

3.3 Robustness and Limitations of the Approaches

The section examines the robustness and limitations of the approaches in this research.

3.3.1 Robustness

3.3.1.1 FRT Application

The robustness of the FRT application has been recorded in the work of Chan et al. (2009). The researchers used a comprehensive literature review based on the application of fuzzy logic /fuzzy set, and hybrid fuzzy techniques in construction management research. The robustness aspects of the FRT application are:

- Ability to model highly complex problems
- Highly appropriate for computational modelling in complex non-linear problems which are poorly understood
- Improved cognitive modelling of expert judgements
- Competency for multiple experts modelling
- Reduced model complexity
- Improved handling of uncertainty

3.3.1.2 FTOPSIS Application

The strength of FTOPSIS has been used in dealing with ranking reversal issues. It performs slightly better than FAHP (Junior et al., 2014; Mousavi et al., 2015). According to Dantsoho (2015), the robustness of the FTOPSIS application is described as follows:

- High computational performance
- Ability to measure the relative performance for each alternative in a simple mathematical form
- Simple and rationally comprehensive concept
- Improved flexibility with large-scale in the definition of the choice set
- Simplified computational process in a spreadsheet

3.3.1.3 FAHP Application

The strengths of FAHP over other multi-criteria methods are its intuitive appeal, flexibility to the decision-makers, and its competency to detect inconsistencies (Javanbarget et al., 2012). In general terms, users find the pairwise comparison form of data input straightforward and convenient (Torfi et al., 2010).

Furthermore, the FAHP technique has the distinct advantage that it breaks down a decision-making problem into its component parts and builds hierarchies of criteria and helps to capture both objective and subjective evaluation measures. While providing a powerful mechanism to check the consistency of the evaluation measures and alternatives, it reduces bias in making a decision (Mahmoodzadehet et al., 2007).

3.3.2 Limitations

3.3.2.1 FRT Application

The limitations of the FRT application which have been outlined in work of Abdelgawad and Fayek (2010), are described as follows:

- Determining and tuning membership functions
- Though easier to design and more prototypical than conventional systems, FRT requires more fine tuning before they are in operation.

- Bias among traditionalists for crisp logic- based systems.

3.3.2.2 FTOPSIS Application

Despite FTOPSIS being one of the most applicable techniques in multiple-criteria decision-making, it is not capable of ranking when there is a substantial number of criteria. Lack of ability to compute the weight of indices is one of the main limitations of this method. Using the FAHP method for the criteria calculation and sub criteria weights eliminates the weakness of the FTOPSIS method (Jato-Espino et al., 2014; Haghshenas et al., 2016).

3.3.2.3 FAHP Application

Despite the popularity of FAHP, some authors have expressed concern regarding certain issues in the FAHP methodology, which are described as follows:

- With AHP the decision making is divided into several subsystems, within which and between which a substantial number of pairwise comparisons need to be completed. This approach has the limitation that the number of pairwise comparisons to be made may become very large (n(n-1)/2), and thus it becomes a lengthy work (Zeng et al., 2007; Chen et al., 2011).
- Another weakness of the AHP technique is the artificial limitation of using of the 9-point scale. Sometimes, the decision-maker might find it difficult to distinguish among them (Macharis et al., 2004).

3.4 Summary

In this chapter, the research methodology has been described which will provide the means to answer the research questions of this thesis by explaining how the gaps will be filled and how to resolve the problems in the existing construction risk management models. To achieve the research aim and objectives, the research project framework design of this study has been adopted. Based on the review of the literature on existing construction safety risk management models, a questionnaire survey will be employed on construction sites to confirm the identified safety risks that were analysed to develop a proposed construction safety risk management model. Before a model was implemented in the specific projects, model testing was used to ensure that the model is conceptually sound and can generate all safety risks efficiently and effectively. Specific project case studies will be carried out to verify the reliability of the proposed construction safety risk management model that could be accepted by the Thai building construction industry.

Finally, group interviews with experienced construction managers and safety managers will be conducted to produce an effective and efficient safety risk management framework in their real construction projects. In the next chapter, the questionnaire will be developed to collect information and find other important safety risks in the Thai building construction industry. The related diagrams and tables will illustrate the results of the questionnaires.

CHAPTER FOUR

SURVEY PROGRAMME

4.1 Introduction

In Chapter 3, the preferred research methodology that has been adopted for this research was discussed, including the research design and Thailand as the chosen case.

This chapter focuses on the questionnaire survey, one of the most powerful research tools for collecting, analysing and interpreting data from a target group (Nardi, 2018). It is used in conjunction with many other methods in survey research. Descriptive statistics and interviews are presented in this chapter, which also provides results confirming the specifications of the hazard groups in the construction industry. The key findings of the survey based upon statistical analysis are also provided.

4.2 Questionnaire Survey Design

A part of the research endeavour to improve safety risk management models for building construction projects, there is a need to identify the various categories of hazard. From this risk criteria can be determined using fuzzy reasoning approaches, allowedly the membership functions of risk parameters such as probability of occurrence, severity of consequence and probability of consequence to be found.

The questionnaire was designed to collect data from project managers, safety managers, safety officers, and site engineers on construction projects. The respondents were asked about the importance of different areas and activities of occupational safety according to their experience. The questionnaire results are used to develop a set of important safety risks and confirm the potential hazards in construction safety risk management models.

4.3 Structure of the Questionnaire

The questionnaire was divided into three main sections:

1. General information
2. Evaluation of 15 safety risks
3. Evaluation of the safety risk parameters of 15 safety risks

A copy of the questionnaire and an example of a completed questionnaire are provided in Appendix A and B respectively. The questionnaire was completed by 42 respondents involved in the building construction industry.

To identify the various categories of hazard that are related to safety risk management models in building construction projects and to develop membership functions of risk parameters such as probability of occurrence, severity of consequence, and probability of consequence, the feedback in sections 1, 2 and 3 of the questionnaire survey needed to be analysed. The general information was investigated by calculating the number and percentage from section 1 in the questionnaire survey. The level of importance of safety risks in construction projects is indicated in section 2 of the questionnaire survey by calculating the weighted average mean scores. In the final section safety risk parameters are defined to measure the probability of occurrence, severity of consequence, and probability of consequence.

4.4 Analysis of the Questionnaire Survey Feedback

This section presents the finding of the questionnaire data. Fifty employees respondents in construction industry projects were contacted, and 42 responses were received. Descriptive statistics are provided, and tables and graphs illustrate the results in the following sections.

4.4.1 General Information

In section 1 of the questionnaire, four questions were asked to capture the general background of the respondents. Table 4-1 shows the distribution of the types of companies. It was found that 73.8 per cent of the companies are contractor companies, the both the government agency and the client account for 4.8 per cent of the total. The results also show that 38.1 per cent of the respondents have 11-15 years' experience, with 33.4 per cent having more than 16 years' experience in this field. This experience is considered potentially profitable for improving the construction performance on the complex project sites. Interestingly, most of the construction types in industry projects are involved in building construction with 92.9 per cent of the total, and 7.1 per cent are involved in either building extension works or building maintenance works as shown in Figure 4-1 and Table 4-1.

Furthermore, the distribution of the roles in the construction industry is also shown in Table 4-1, which reveals that 35.7 per cent of the survey respondents are project managers, 30.9 per cent are engineers, and 23.8 per cent are safety officers.

Table 4-1: The general information of respondents

Type of company			Years of experience			Type of construction industry projects			Role in construction industry		
Category	Number of people	Percentage	Number of years	Number of people	Percentage	Category	Number of people	Percentage	Category	Number of people	Percentage
Consultant	4	9.5%	1-5	4	9.5%	Building construction	39	92.9%	Project manager	15	35.7%
Contractor	31	73.8%	6-10	8	19.0%	Building extension works	1	2.4%	Engineer	13	30.9%
Developer	3	7.1%	11-15	16	38.1%	Building maintenance works	2	4.7%	Planner	1	2.4%
Government agency	2	4.8%	16-20	7	16.7%				Contractor	1	2.4%
Client	2	4.8%	More than 20	7	16.7%				Safety officer	10	23.8%
									Senior inspector and construction supervisor	2	4.8%
Total	42	100%	Total	42	100%	Total	42	100%	Total	42	100%

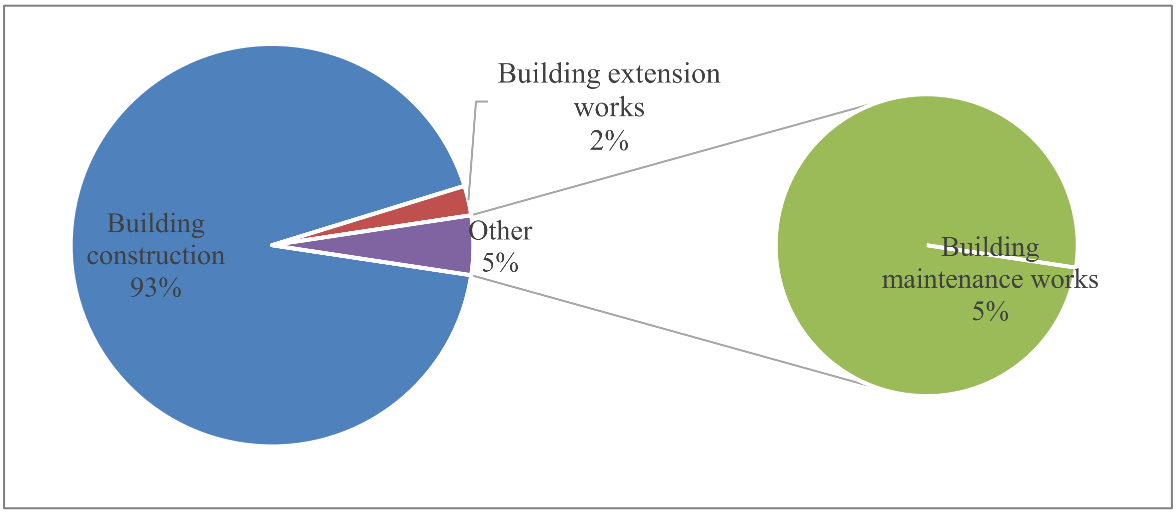


Figure 4-1: Types of construction industry projects

4.4.2: Evaluation of 15 Safety Risks

The second part of the questionnaire contained questions about the safety risks identified from the literature review. Respondents were asked to give one of five scores for each of 15 safety risks to indicate their importance (1= low importance to 5 = high importance). The experience factor of 42 respondents with different backgrounds and experience in this subject who are involved in the construction projects is illustrated in Table 4-2.

Table 4-2: Respondents' experience factors

Respondent groups	Years of experience	Score	Contribution factor
C_1	1-5	1	0.10
C_2	6-10	2	0.15
C_3	11-15	3	0.20
C_4	16-20	4	0.25
C_5	20+	5	0.30

The level of importance of each hazard group was measured in five interval levels on a Likert scale. The range was obtained based on manual scoring to obtain the division of scores, for example, "Less important" can be calculated by (5-1=4/5+1=1.8), as shown in Table 4-3.

Table 4-3: The importance of the hazard groups

Title	Description	Ranges
Very important	Extremely important in project construction industry	4.21-5.00
Major	Highly important in project construction industry	3.41-4.20
Average	Has impact on project construction industry	2.61-3.40
Minor	Has little impact on project construction industry	1.81-2.60
Less important	Has no or very little impact	1.00-1.80

Fifteen hazard groups that were believed to have an influence on risk identification and prevention were identified through a literature review in Section 2.4.2 of Chapter 2 and in the second section of the questionnaire. These 15 safety risks are listed as shown in Table 4-4, and a short definition of each of them is provided.

Table 4-4: The definition of the 15 hazard groups

Hazard group	Descriptions
Falls from height	Workers are typically required to work at heights on the construction sites. These heights include both temporary structures such as scaffolding and permanent structures such as roofs
Falling objects	Objects falling from work ladders, platforms, scaffolds or mobile scaffolding. Debris from grinding operations. Wind blown particles
Manual handling	The movement of loads by worker effort alone. It can include any activity that requires overload by workers by lifting, pushing, pulling or carrying
Equipment, machinery, tools	Most of the equipment used on site can be hazardous as it could strike construction workers while at work
Electricity	Contact with overhead electric power lines and building power constitutes the most common source of electric shock
Slips and trips	Trips and slips happen due to lack of awareness, poor attention to detail, absence of signage and markings, poor illumination, slippery surfaces, and access routes obstructed by materials
Traffic hazards	Working in close proximity to roads, trucks entering or reversing on construction sites
Fire and explosions	These could occur due to a ruptured utility gas line, flammable fumes, and electrical connections to the construction site

Table 4-4: The definition of the 15 hazard groups (cont.)

Hazard group	Descriptions
Exposure to hazardous substances	Exposure to hazardous substances such as silica dust, asbestos, and solvent
Radiation hazards	Exposure to arc welding or exposure to or generation of lasers
Vehicle overturn	Crane overturn, mobile plant overturn, such as tractors, dumper trucks, forklifts and Bobcats
Collapse of site structure	Collapse of booms, scaffolding or other temporary structural or load-bearing components
Noise and vibration	Noise comes from the operation of plant, machinery and power tools, the movement of vehicles, and the delivery of materials
Confined spaces	Entering tunnels, hoppers, vats, tanks or pits to inspect or test, work or clean
Ergonomic/Human Factors	Poor work posture, repetitive movement, and handling of heavy objects

The respondents were grouped into five categories: 1-5, 6-10, 11-15, 16-20, and 20+ years' experience, respectively. Based on the questionnaire survey data, the level of importance of the risk was calculated based on the questionnaire survey data.

The data collected from the questionnaire survey was calculated according to the average score, as performed by Priyadarshani et al. (2013):

$$\text{Average score} = \frac{\sum f \times s}{N} \qquad \text{Eq. 4-1}$$

where f = Frequency of responses rating each risk

s = Score given to each risk by the respondents, and

N= Total number of responses concerning that risk.

For example, the results of the average score for the 15 risks (C_5 = more than 20 years' experience) are illustrated in Table 4-5.

Table 4-5: Number and percentage of the safety risks in construction (C_5 = more than 20 years' experience)

Safety risks	Level of importance (1=Low to 5=High)					Average
	1 (%)	*2* (%)	*3* (%)	*4* (%)	*5* (%)	
Falls from height (FH)	-	-	-	1(14.29)	6(85.71)	4.86
Falling object (FO)	-	-	1(14.29)	2(28.57)	4(57.14)	4.43
Manual handling (MH)	-	2(28.57)	2(28.57)	-	-	2.71
Equipment, machinery (EM)	-	-	4(57.14)	1(14.29)	4(57.14)	4.29
Electricity (EL)	-	-	3(42.86)	2(28.57)	1(14.29)	3.57
Slips and trips (ST)	-	-	3(42.86)	3(42.86)	1(14.29)	3.71
Traffic hazards (TH)	2(28.57)	1(14.29)	4(57.14)	-	1(14.29)	2.57
Vehicle overturn (VO)	1(14.29)	1(14.29)	3(42.86)	-	1(14.29)	2.86
Fire and explosions (FE)	2(28.57)	-	2(28.57)	1(14.29)	1(14.29)	2.86
Exposure to hazardous substances (ES)	3(42.86)	1(14.29)	1(14.29)	-	1(14.29)	2.29
Radiation hazards (RH)	4(57.14)	1(14.29)	-	-	1(14.29)	2.00
Collapse of site structure (CO)	2(28.57)	-	1(14.29)	3(42.86)	2(28.57)	3.43
Confined spaces (CS)	2(28.57)	2(28.57)	3(42.86)	1(14.29)	1(14.29)	2.57
Ergonomic/human factors (EH)	1(14.290	3(42.86)	2(28.57)	-	-	2.29
Noise and vibration (NV)	4(54.14)	1(14.29)		-	-	1.71

Table 4-6 also shows the results of the mean value with their corresponding weightings and can be calculated by Equation (4-1):

$$FH_{WA} = 0.10\times4.50+0.15\times4.25+0.20\times4.19+0.25\times4.86+0.30\times4.86 = 4.60$$

FO_{WA} = 0.10×3.50+0.15×4.38+0.20×3.75+0.25×4.43+0.30×4.43 = 4.19

MH_{WA} = 0.10×2.75+0.15×2.88+0.20×3.31+0.25×3.57+0.30×2.71 = 3.08

EM_{WA} = 0.10×3.50+0.15×3.38+0.20×3.69+0.25×4.29+0.30×4.29 = 3.95

EL_{WA} = 0.10×3.50+0.15×3.50+0.20×3.50+0.25×4.00+0.30×3.57 = 3.65

ST_{WA} = 0.10×3.00+0.15×3.00+0.20×3.44+0.25×3.29+0.30×3.71 = 3.37

TH_{WA} = 0.10×2.50+0.15×2.50+0.20×2.50+0.25×3.29+0.30×2.57 = 2.72

VO_{WA} = 0.10×3.00+0.15×2.63+0.20×2.56+0.25×2.86+0.30×2.86 = 2.78

FE_{WA} = 0.10×3.25+0.15×2.63+0.20×3.00+0.25×3.57+0.30×2.86 = 3.07

ES_{WA} = 0.10×2.75+0.15×2.13+0.20×2.44+0.25×3.57+0.30×2.29 = 2.66

RH_{WA} = 0.10×2.75+0.15×1.75+0.20×2.00+0.25×2.14+0.30×2.00 = 2.07

CO_{WA} = 0.10×3.25+0.15×3.13+0.20×3.13+0.25×3.86+0.30×3.43 = 3.41

CS_{WA}= 0.10×3.75+0.15×3.88+0.20×3.38+0.25×3.29+0.30×2.57 = 3.22

EH_{WA} = 0.10×3.50+0.15×3.13+0.20×3.00+0.25×2.57+0.30×2.29 = 2.75

NV_{WA} = 0.10×3.50+0.15×3.00+0.20×2.88+0.25×2.86+0.30×1.71 = 2.60

where FH_{WA}, FO_{WA}, MH_{WA}, EM_{WA}, EL_{WA}, ST_{WA}, TH_{WA}, VO_{WA}, FE_{WA}, ES_{WA}, RH_{WA}, CO_{WA}, CS_{WA}, EH_{WA}, and NV_{WA} are the weighted average mean value of corresponding items shown in Table 4.5 respectively.

It can be seen from the data analysis that the survey respondents indicated that falls from height is a very important risk on construction sites, with a weighted average value of 4.6.

Table 4-6: Weighted average mean score of the safety risk level on construction projects

Safety risks	Weighted average value					Weighted average	Level of importance
	C_1 (0.10)	*C_2* (0.15)	*C_3* (0.20)	*C_4* (0.25)	*C_5* (0.30)		
FH	4.50	4.25	4.19	4.86	4.86	4.60	Very important
FO	3.50	4.38	3.75	4.43	4.43	4.19	Major
MH	2.75	2.88	3.31	3.57	2.71	3.08	Average
EM	3.50	3.38	3.69	4.29	4.29	3.95	Major
EL	3.50	3.50	3.50	4.00	3.57	3.65	Major
ST	3.00	3.00	3.44	3.29	3.71	3.37	Average
TH	2.50	2.50	2.50	3.29	2.57	2.72	Average
VO	3.00	2.63	2.56	2.86	2.86	2.78	Average
FE	3.25	2.63	3.00	3.57	2.86	3.07	Average
ES	2.75	2.13	2.44	3.57	2.29	2.66	Average
RH	2.75	1.75	2.00	2.14	2.00	2.07	Minor
CO	3.25	3.13	3.13	3.86	3.43	3.41	Major
CS	3.75	3.88	3.38	3.29	2.57	3.22	Average
EH	3.50	3.13	3.00	2.57	2.29	2.75	Average
NV	3.50	3.00	2.88	2.86	1.71	2.60	Minor
Number (n)	4	8	16	7	7		

This result is consistent with the finding of Mistikoglu et al. (2015), which was that falls from height was the most important characteristic increasing the chance of fatality in the construction industry due to a fall protection system not being implemented.

The respondents were asked to add other risks that they thought were important on construction sites but were not listed in the questionnaire survey. Some of the safety risks they mentioned are: (1) Lighting; (2) Lack of skills; (3) Site environment; (4) Platforms that become holes; and (5) PPE.

The final section of the questionnaire to be analysed is the membership functions of three parameters for the five-point scale of linguistic statements as shown in Table 4-7. The respondents were asked about the probability of occurrence, severity of consequence and probability of consequence, and the proportion for defining the number of safety risks is provided by ticking two, three or four numbers to construct the fuzzy membership function. The degree of fuzzy membership can be calculated as

$$Z(X) = \frac{P(X_i)}{N} \quad \text{Eq. 4-2}$$

where $Z(X)$ is the degree of fuzzy membership, $P(X_i)$ is the number of positive replies, and N is the total number of responses.

4.4.3 Evaluation of the Membership Functions of Three Parameters

As Table 4.7 shows, regarding the probability of occurrence, more than 57 per cent of the respondents considered that falls from height is likely and 74 per cent considered that falling objects is very likely more than radiation hazards, traffic hazards and confined space. Considering the severity of consequence, falls from height 86 per cent of the respondents considered that falls from height and 76 per cent of the respondents considered that collapse of site structure are catastrophic than manual handling, slips and trips, traffic hazards, ergonomic/human factors, and noise and vibration. Regarding the probability of consequence, 57 per cent of the respondents considered that falling objects is reasonably likely and 43 per cent considered that it is highly likely.

Table 4-7: Membership functions (MF*f*) from surveying respondents

Safety Risk	Probability of occurrence					Severity of consequence					Probability of consequence					
	Very unlikely	Unlikely	Fairly unlikely	Likely	Very likely	Negligible	Minor	Moderate	Major	Catastrophic	Highly unlikely	Unlikely	Reasonably unlikely	Likely	Reasonably likely	Highly likely
Falls from height	0.00	0.02	0.19	0.57	0.52	0.00	0.02	0.12	0.38	0.86	0.00	0.10	0.24	0.29	0.40	0.43
Falling objects	0.00	0.02	0.01	0.50	0.74	0.00	0.12	0.33	0.55	0.57	0.00	0.02	0.12	0.40	0.57	0.43
Manual handling	0.10	0.24	0.36	0.48	0.14	0.12	0.48	0.48	0.36	0.00	0.02	0.19	0.48	0.50	0.14	0.05
Equipment, machinery, tools	0.02	0.21	0.45	0.45	0.21	0.02	0.21	0.43	0.48	0.33	0.02	0.19	0.31	0.45	0.29	0.19
Electricity	0.12	0.21	0.36	0.48	0.21	0.05	0.17	0.31	0.40	0.55	0.07	0.26	0.36	0.38	0.17	0.21
Slips and trips	0.07	0.26	0.29	0.50	0.17	0.19	0.48	0.38	0.17	0.17	0.07	024	0.38	0.31	0.33	0.17
Traffic hazards	0.21	0.29	0.33	0.33	0.00	0.17	0.36	0.33	0.38	0.17	0.19	0.31	0.38	0.29	0.17	0.00
Vehicle overturn	0.31	0.31	0.31	0.31	0.02	0.17	0.17	0.33	0.38	0.38	0.21	0.38	0.36	0.24	0.14	0.02
Fire and explosions	0.21	0.21	0.33	0.38	0.12	0.07	0.07	0.24	0.45	0.52	0.17	0.33	0.29	0.29	0.17	0.14
Exposure to hazardous substances	0.33	0.26	0.33	0.26	0.07	0.17	0.24	0.26	0.38	0.31	0.21	0.31	0.24	0.21	0.17	0.07
Radiation hazards	0.57	0.24	0.14	0.14	0.05	0.19	0.14	0.14	0.43	0.40	0.31	0.52	0.19	0.14	0.02	0.07
Collapse of site structure	0.29	0.24	0.26	0.26	0.17	0.07	0.02	0.17	0.04	0.76	0.31	0.19	0.24	0.29	0.14	0.17
Confined spaces	0.10	0.36	0.26	0.29	0.21	0.10	0.17	0.31	0.48	0.48	0.10	0.45	0.26	0.29	0.14	0.10
Ergonomic/human factors	0.12	0.26	0.33	0.40	0.12	0.05	0.50	0.45	0.24	0.07	0.17	0.24	0.33	0.26	0.29	0.07
Noise and vibration	0.10	0.19	0.43	0.45	0.17	0.12	0.43	0.50	0.31	0.00	0.12	0.29	0.38	0.31	0.29	0.07

Comments made by respondents:

The following points relate to the question "Do you have any other comments about this research project either relating to the previous questions, or otherwise?"

1. Some respondents do not use any statistical methods to assess the safety risks on construction projects. Experience and subjective assessment are the only techniques that are being employed in risk safety management.
2. "Make empirical formulas for safety risk management in building important."
3. Employers should emphasise occupational safety.
4. This research is an interesting new study on safety risk assessment methods.
5. "Safety risk assessment on construction projects is important."
6. "This project should not only consider the type of company that does construction work, but also define the root of safety risk."
7. This is good research because the safety risks on construction projects will be identified, assessed, and controlled in the construction industry.

4.5 Summary of Findings

Most of the findings of this survey are not surprising; however, some of them are important and need to be highlighted. A summary of the important findings from the questionnaires is provided below.

The study found that, falls from height is considered to be a very important safety risk and that falling objects; equipment, machinery and tools; electricity; and collapse of site structure are considered to be more major safety risks than radiation hazards and noise and vibration.

The opinions, suggestions and recommendations provided by the respondents to the questionnaire provided an excellent resource for the development of safety risk management models to implement risk management strategies for building construction projects. The results of the questionnaire survey can be summarised as follows:

- It has been shown that the identification of construction site hazards is one of the most important techniques used to assess existing safety risks. Safety risk analysis and management needs to be undertaken before a project is started and continue until the project is completed. Because of the dynamic nature of construction activities, the environment is continuously changing with fast-moving features, different stages, and a huge number of project participants, such as contractors, subcontractors, and clients.
- Safety observations and inspections on the construction sites provide a means to identify what could cause harm. Walked inspections are designed to identify hazards and should be considered to improve working conditions and ensure that safety procedures are meeting the required standard or law, for example, a safety inspector shall have authority to inspect or record images or noises in the workplace that concern safety, occupational health and the workplace
- An important influence in reducing the number of major incidents is an effective incident reporting process to look back at the less obvious hazards. Moreover, accident records need to be kept and investigations undertaken as soon as possible to control risk and prevent accidents recurring. This is not intended to lay blame but should focus on prevention. Near misses also need to be recorded and investigated to gain a full understanding of risk.
- Seeking safety risk information from other sources such as occupational safety websites, including http://www.hse.gov.uk, https://www.osha.gov, http://www.mol.go.th, http://www.nsc.org, and http://www.shawpat.or.th can be

useful. Furthermore, documented safety standard operating procedures (SSOP) are necessary to ensure compliance with various legal requirements. This safety guidance is provided to ensure that safety at work is respected and managed for defining and documenting appropriate control methods to minimise the potential for accidents or injuries.

- Risk assessments are central to managing occupational safety in construction projects. They should always be carried out by an expert who is experienced and competent to do so. Competence can be defined as a combination of knowledge, awareness, training, and experience. Moreover, risk assessments need be reviewed on a regular basis, weekly, monthly, yearly, depending on risk or if something changes, such as a change in production or process or a new worker.
- Risk is defined as the likelihood that a hazard will cause harm, which is defined as Safety risk = Likelihood × Severity (Fung et al., 2010; Anbari et al., 2015). Numerical scores are given to the severity and likelihood of risks, and these scores are multiplied to obtain a rating for the risk.

CHAPTER FIVE

CONCEPTS OF FRT, FUZZY AHP AND FUZZY TOPSIS

5.1 Introduction

In this chapter, the concepts of the FRT, FAHP and FTOPSIS are outlined. Section 5.2 describes the background of the FRT. The AHP, FAHP and MFAHP are described in section 5.3. Section 5.4 describes the traditional TOPSIS and FTOPSIS methods. At the end of this chapter, conclusions are presented.

5.2 Fuzzy Reasoning Technique (FRT)

The FRT, based upon the concept of fuzzy logic and classical fuzzy sets, has been proposed by Zadeh in 1979 for processing uncertain information or imprecise knowledge in fuzzy expert systems as problems frequently involve a human factor, subjectivity. Conventional mathematics cannot solve problems including both qualitative and quantitative variables. With the FRT, the objective function of linguistic variables can be transformed into quantitative data. The process of transformation is illustrated in Figure 5-1.

The Figure 5-1 indicates that the FRT increases the efficiency of the environment and the fuzziness of information in solving practical problems. Therefore, the application of the fuzzy reasoning method has been employed in a wide variety of subject areas, especially in risk assessment (Zeng et al., 2007; An et al., 2011, Nieto-Morote and Ruz-Vila (2011), Taylan et al., 2014).

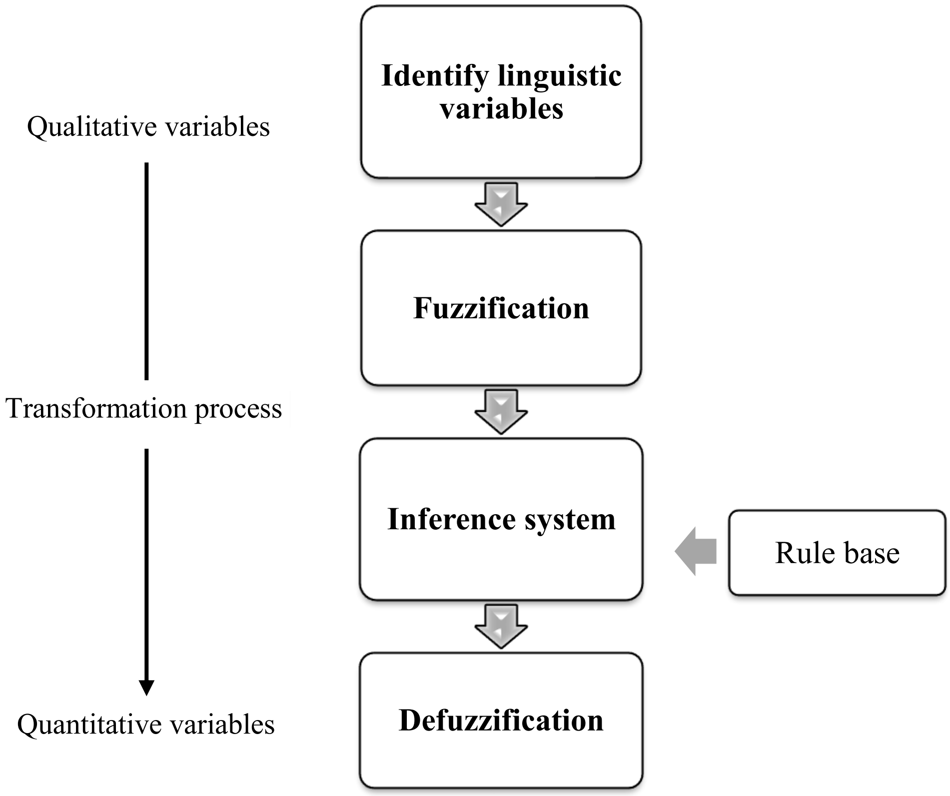


Figure 5-1: Flowchart for the transformation process

5.2.1 Introduction to Fuzzy Set Theory

The concept of fuzzy sets and fuzzy logic was first introduced by Zadeh in 1965, when he published his work "*Fuzzy Sets*" to provide a model for dealing with the subjective judgement, uncertainty, and imprecision associated with data in risk assessment. The concept has been used in many areas related to both qualitative information and quantitative data in a uniform manner. Fuzzy logic theory is a branch of set theory that uses degree of membership in a set rather than strict true or false membership. Fuzzy logic is originally concerned with quantifying and reasoning with defined or vague linguistic terms, for example, good condition, likely, major risk. These terms are difficult to define meaningfully with a precise single value. Therefore, fuzzy logic is formally defined in a mathematical set. The basic fuzzy logic system includes four stages; fuzzification, fuzzy rule base, fuzzy inference system, and defuzzification, as shown in Figure 5-2 (Zeng et al., 2007; An et al., 2011).

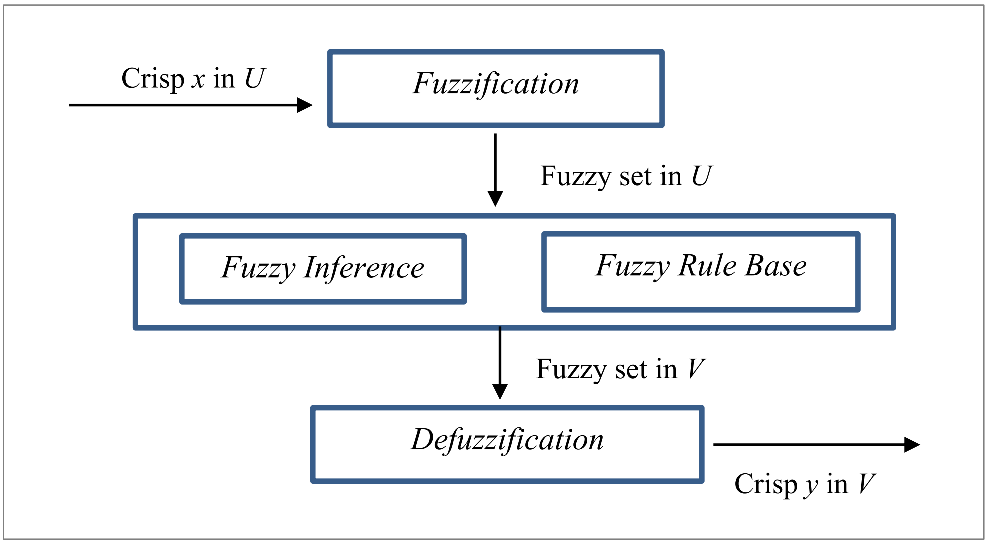


Figure 5-2: The basic fuzzy logic system

5.2.2 Fuzzy Sets

The idea of a fuzzy set is fundamental to mathematics (Zadeh, 1965). A fuzzy set is a set with vague, unsharp boundaries. It is known in terms of a membership function which is drawn from the universe discourse U for an interval of [0, 1]. A traditional function is a case of a membership function and a regular set (a *crisp set*) is a special case of a fuzzy set. However, the idea of a fuzzy set is a gradual interval with fixed limits concept used in traditional set theory. Fuzzy logic is an alternative to the classic set where every proposition must be either “False” (0) or “True” (1). Figure 5-3 shows the difference between a fuzzy set and a classic set. Point *a* in Figure 5-3, the crisp set A is clearly a member; point *b* is unambiguously not a member of set A. Conversely, point *a* in fuzzy set B is clearly a full member. Nevertheless, the boundary region of fuzzy point *b* is clearly not a member. However, point *c* in fuzzy set B is vague. Thus, the membership function in a fuzzy set is a number between 0 and 1.

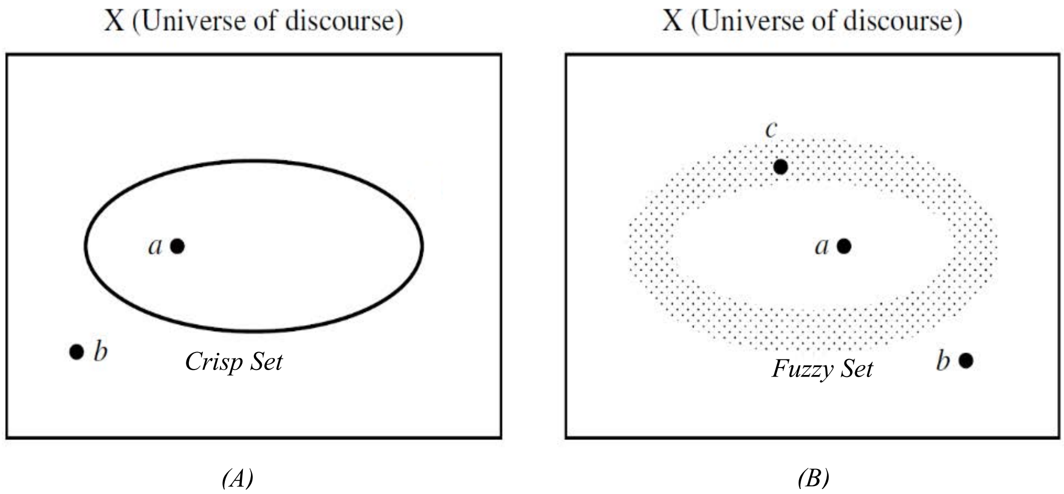


Figure 5-3: The crisp set boundary and fuzzy set boundary (reproduced from Ross, 2009)

- Definition: (Intersection) The membership function $\mu_{C(x)}$ of set C = A ∩ B is defined as $\mu_{C(x)} = \min \{\mu_{A(x)}, \mu_{B(x)}\}$, $x \in$ X.
- Definition: (Union) The membership function $\mu_{C(x)}$ of C = A ∪ B is defined as $\mu_{C(x)} = \max \{\mu_{A(x)}, \mu_{B(x)}\}$, x ∈ X.
- Definition: (Complement) The membership function of the complement of fuzzy set A, $\mu_{A'(x)}$ is defined as $\mu_{A'(x)} = [1 - \mu_{A(x)}]$, $x \in$ X.

5.2.3 Membership Function (MF_f)

The membership function is considered as the most important component of the fuzzy method. It can handle imprecision, and ambiguity in quantitative data and qualitative information in a uniform manner (Zeng et al., 2007). Various types of MF_f can be manipulated, such as trapezoidal membership functions, triangular membership functions, generalised bell-shaped functions, and Gaussian functions. However, trapezoidal and triangular membership functions are the simplest types and also have been used frequently in fuzzy set applications.

A triangular MF_f is a function of μA(x) that depends on the scalar parameter *a* as a lower limit, *c* as an upper limit, and a< b<c Figure 5-4 presents the diagram and formula of a triangular membership function. A triangular MF_f can be defined as *A= {a,b.c}*

$$\mu A(x) = \begin{cases} 0, x \le a \\ (x-a)/(b-a), x \in (a,b) \\ (c-x)/c-b), x \in (c,b) \end{cases} \quad \text{Eq. 5-1}$$

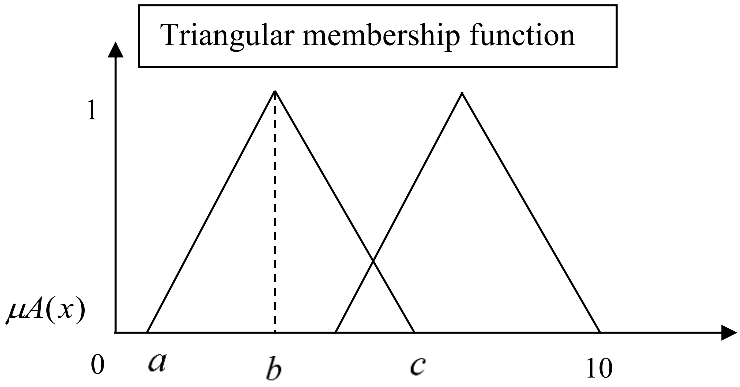


Figure 5-4: Illustration of triangular membership function (MF_f)

A trapezoidal MF_f is employed to convert the judgement of an expert into a universal format for the composition of group preferences as shown in Figure 5-5. It can be defined as X= (*a*, *b*, *c*, *d*), where its membership function indicates the degree of preference that is defined as

$$\mu_A(x) = \begin{cases} 0, x \le a \\ (x-a)/(b-a), x \in (a,b) \\ 1, x \in (b,c) \\ (d-x)/d-c), x \in (c,d) \\ 0, x \ge d \end{cases} \quad \text{Eq. 5-2}$$

where *A* set of real numbers (*a*, *b*, *c*, *d*) with the relationship's satisfaction $a \le b \le c \le d$ determines the *x* coordination of the four points of a trapezoidal MF_f.

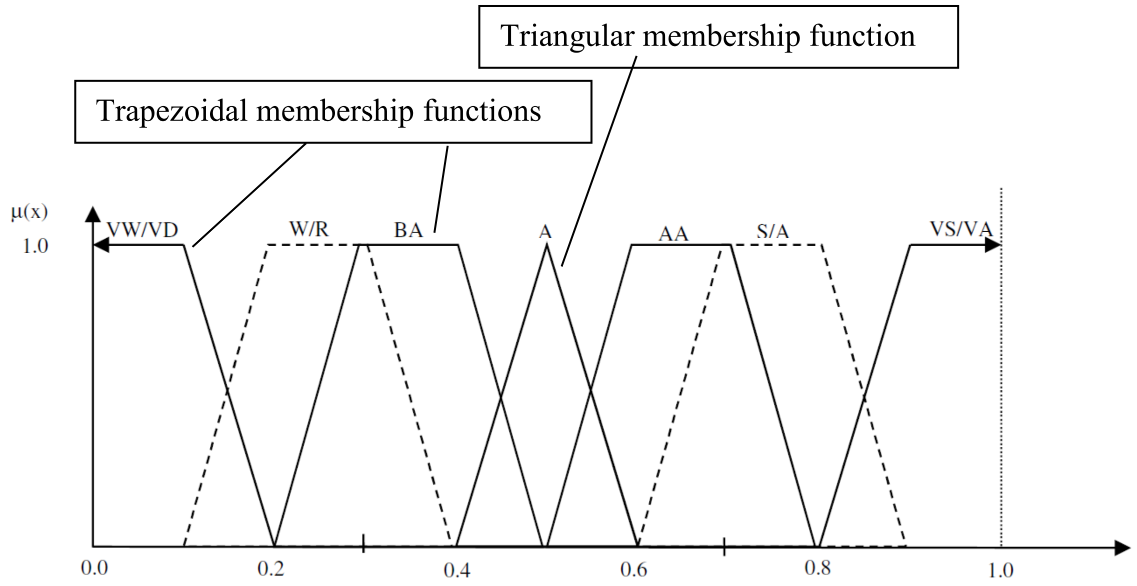


Figure 5-5: Illustration of trapezoidal and triangular MF_f

(reproduced from Leśniak and Plebankiewicz, 2013)

5.2.4 Fuzzification

The fuzzification process is the process of changing a real scalar value into a fuzzy set of values based on its MF_f. The fuzzification process allows the input into the system to be expressed in linguistic terms (Zeng et al., 2007, Idrus et al., 2011). For example, the freezing point of water is 32 F°. It is a member of the freezing water set with a degree of membership of 0.7. However, it is also a member of the cool water set with a degree of 0.3, as shown in Figure 5-6

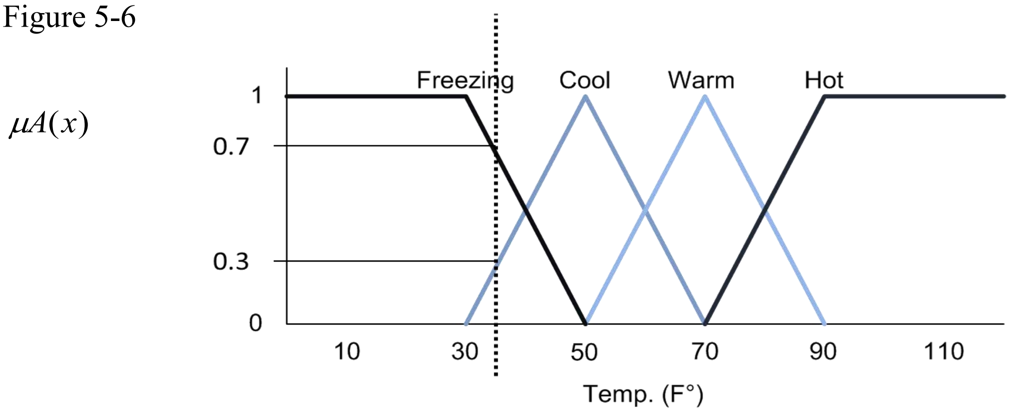


Figure 5-6: Fuzzy sets of the freezing point of water is 32 F°

(reproduced from Deng and Nickerson, 2013)

5.2.5 Fuzzy Rule Base

A rule-based system is a conditional statement written in the *If A then B* form, where *A*, and *B* are linguistic variables. *A* is called the antecedent and *B* fuzzy is the consequent of the rule (Idrus et al., 2011). The development of the fuzzy rule base may be acquired based on historical data on the information in the previous accidents and incidents database system, concept mapping, and expert judgement (An et al., 2011). For many practical situations, several approaches can be used to generate a body of information that may also be helpful in developing fuzzy linguistic variables. Fuzzy rules provide a natural platform for abstracting information based on domain human expert knowledge and engineering judgement. Therefore, experts often consider fuzzy rules to be a suitable way to express their knowledge of a situation.

$$Ri: \text{ IF } x_1 \text{ is } A_1 \text{ and } x_2 \text{ is } A_2 \text{ and} \ldots\ x_n \text{ is } A_n \text{, THEN } y \text{ is } B \qquad \text{Eq. 5-3}$$

In the above equation $x_1, x_{2,\ldots,} x_n$ represent the input variables to the rule, y is the output variable, and $A_1, A_2, \ldots, A_n$ are fuzzy sets.

For example, the *Ri* Rule can be explained as:

Ri: IF *Probability of occurrence* is *Very likely* and *Severity of consequence* is *Major* and *Probability of consequence* is *Highly likely* THEN *Risk level* is *Unacceptable*

5.2.6 Fuzzy Inference

Fuzzy inference is the process of transforming given input values into a determined output using fuzzy logic (Beriha et al., 2012). Mamdani’s fuzzy inference method is the most commonly used fuzzy methodology. Consider the following rules:

Rule#1: *If x is* X_3 *and y is* Y_1*, then z is* Z_1

Rule#2: *If x is* X_2 *and y is* Y_2*, then z is* Z_2

Rule#3: *If x is* X_1*, then z is* Z_3

For example,

Rule #1: If *site safety* is adequate and *the number of safety officers* is small, *then safety risk* is low

Rule #2: If *site safety* is marginal and *the number of safety officers* is large, *then safety risk* is acceptable

Rule #3: *If site safety is* inadequate, *then safety risk is* high

where *x*, *y* and *z* are site safety, the number of safety officers and safety risk of the linguistic variables; *X*1, *X*2 and *X*3 are inadequate, marginal and adequate of the linguistic values; *Y*1 and *Y*2 are small and large; and *Z*1, *Z*2 and *Z*3 are low, acceptable and high of the linguistic values.

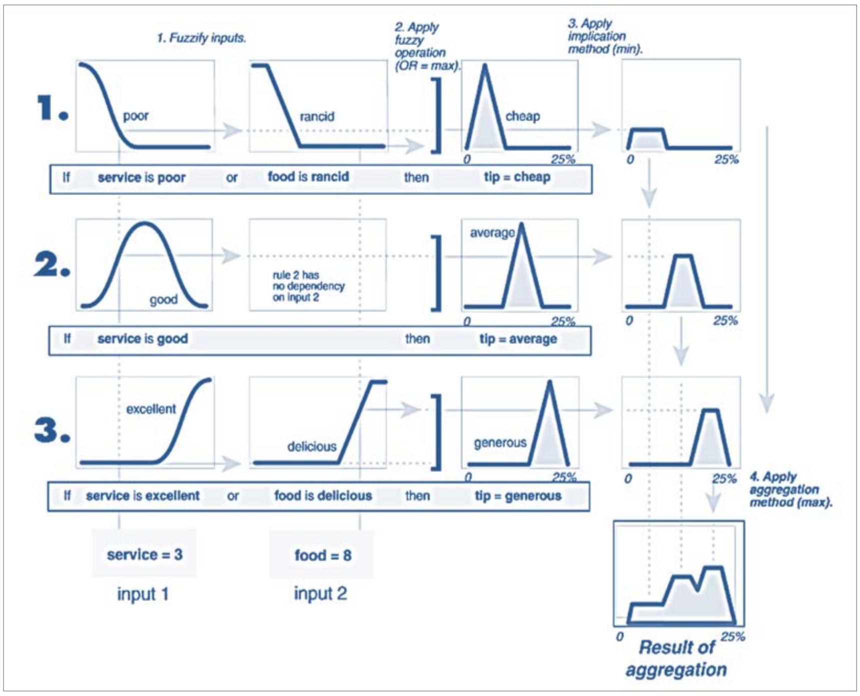


Figure 5-7: The basic structure of Mamdani's fuzzy inference method (reproduced from MathWorks, 2015)

5.2.7 Defuzzification

After the aggregation step, the final result is defuzzified into a crisp number that drives the system. During the defuzzification, a fuzzy centroid method or centre of gravity is the most prevalent and used to defuzzify the aggregated result into a crisp output as shown in Figure 5-8 (Zeng et al., 2005; Beriha et al., 2012), defined as

$$Z^* = \frac{\int_y \mu A(Z) Z dz}{\int_y \mu A(Z) dz} \qquad \text{Eq. 5-4}$$

where $\mu_A(Z)$ is the aggregated output membership function.

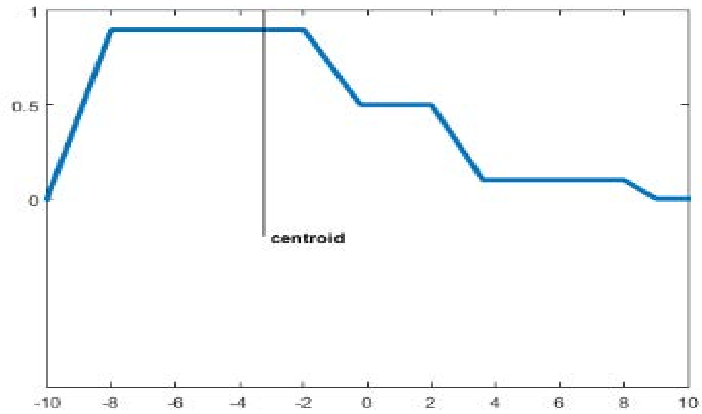


Figure 5-8: The fuzzy centroid method (reproduced from Zeng et al., 2005)

5.3 Modified Fuzzy Analytical Hierarchy Process (MFAHP)

The MFAHP has been developed based on the traditional AHP. This section provides the details of the development.

5.3.1 Analytical Hierarchy Process (AHP)

The AHP, which was developed by Saaty in 1980, is a quantitative technique based on mathematics to solve many complicated decision-making problems using a hierarchical structure (Taylan et al., 2014). Nowadays, it is used around the world in a wide variety of way to solve MCDM problems, such as, business, industry, and health and safety, which helps in setting their priorities (Badri et al., 2012; Aminbakhsh et al., 2013). The AHP has also been used for identifying and weighting in the field of project risk assessment (Zeng et al., 2007, An et al., 2011; Nieto-Morote and Ruz-Vila, 2011). This structured technique works by minimising complex evaluation criteria into a series of one-to-one pairwise comparisons (Taylan et al., 2014).

The steps of the traditional AHP technique are described briefly below (Bhushan and Rai, 2007):

1. The problem is decomposed into its constituent parts.
2. A hierarchy is a hierarchical system of ranking and organising, for example, all elements of the complex relationships shown in Figure 5-9.

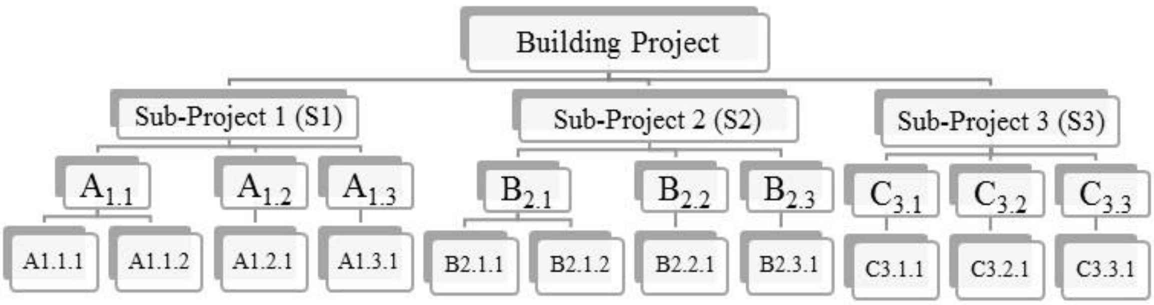


Figure 5-9: Example of the hierarchical structure used for construction risk projects

3. Data are collected from experts, and is required to compare with questions such as ‘How strongly important does S1 dominate S2?’ on a ratio scale between 1 (equally important) and 9 (absolutely important) to the more important criterion, as shown in Figure 5-10
4. The pairwise comparisons of various criteria are generated into a square matrix.
5. The principal eigenvalue is used to find the relative weights of the elements.

6. The rating of the elements is computed and aggregated to obtain the final ratings.

Hazard group 1 (S1)									**Hazard group 2 (S2)**							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9
Hazard group 2 (S2)									**Hazard group 3 (S3)**							
9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9

Figure 5-10: Example of the AHP questions

Regardless of the method used to collect the data from the experts in the traditional AHP technique sometimes experts are unable to compare two factors or are unable to give the exact crisp numbers when conducting the pairwise comparisons as they are not confident of the degree of importance (Janackovic et al., 2013; Abdullah and Zulkifli, 2015; An et al., 2016). For example, expert#1 knows that criterion S1 is more strongly important than criterion S2 due to a lack of certainty regarding information and difficulty in capturing uncertain and imprecise. The experts probably give a range of numbers between 6 and 8 to describe these criteria.

Therefore, the traditional AHP method seems inadequate to capture experts' judgements clearly. To deal with problems relating to subjective judgement, uncertainty and imprecision associated with data in safety risk assessment the FAHP, which is described in Section 5.3.2, can handle the uncertainty and ambiguity associated with linguistic terms in a uniform manner.

5.3.2 Fuzzy Analytical Hierarchy Process (FAHP)

The FAHP technique, which first appeared in Laarhoven and Pedrycz in 1983, uses triangular membership functions which are compared with fuzzy ratios instead of crisp data as in

Saaty's research. Buckley (1985) determined the fuzzy priorities of comparison ratios of fuzzy trapezoidal membership functions. This reduces the subjectivity of human judgement by using more uniform expressions, provides a more flexible approach to the pairwise comparison process by playing a key role in handling this issue, and allows the experts to cope with imprecise, ambiguous data in the decision process. Consequently, the linguistic terms have been used to help the experts to reach a conclusion. Chang (1996) developed a new method for engaging group decisions using the FAHP technique based on triangular fuzzy numbers, as shown in Figure 5-11. Furthermore, many AHP methods developed by various authors have been described in Chapter 2.

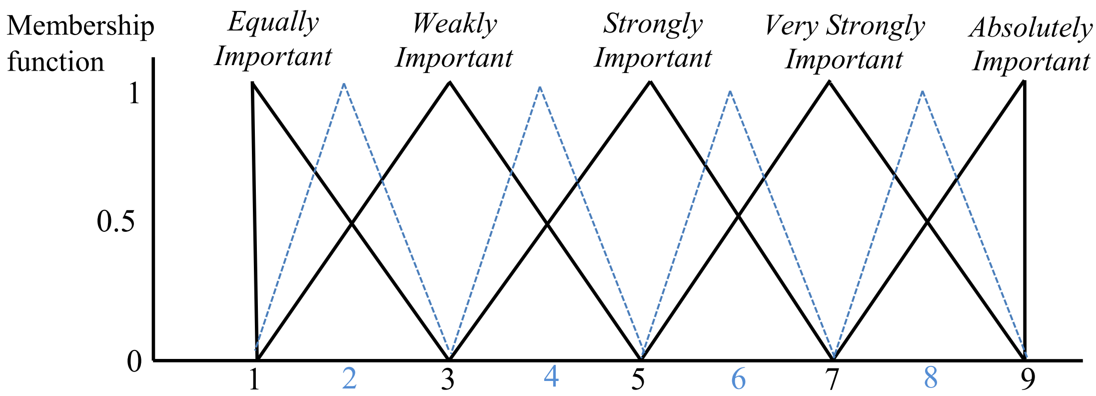


Figure 5-11: Linguistic variables of triangular fuzzy numbers
(reproduced from Ibadov et al., 2013)

Nevertheless, the field of project risk evaluation often involves a large number of pairwise comparison metrics in the decision process. Basically, when applying FAHP, the pairwise comparison can be obtained as n (n-1)/2 comparisons (Chen et al., 2011). The width of pairwise comparison metrics increases as the number of pairwise comparison metrics increases. Consequently, the judgements are based on the expert's experience and engineering knowledge, and there may be a lack of confidence that all comparisons are correctly justified in a precise way. Furthermore, inconsistent conclusions do not provide the lack of confidence to make a decision. The MFAHP is described in Section 5.3.3.

5.3.3 Modified Fuzzy Analytical Hierarchy Process (MFAHP)

The MFAHP technique was used to synthesise the opinions of experts to identify the fuzzy weights of each criterion. It was developed for creating a consistent pairwise comparison matrix from a set of *n*-1 judgements that generates a huge requirement for expert judgement and reduces the consistency of results. It should be suitable technique for tackling practical MCDM problems and is more appropriate and effective than FAHP in real practice when there are a huge number of comparisons. (An et al., 2016).

It should be noted that in this thesis, the MFAHP method is employed for calculating the favourable weight of fuzzy linguistic variables and fed into FTOPSIS to construct the safety risk management model, which will be outlined in Chapter 6.

The steps of the MFAHP procedure to compute the fuzzy weights are as follows:

1. Construct a pairwise comparison matrix from a panel of experts. The judgements of pairwise comparison are synthesised regarding the degree of importance by linguistic variables. A corresponding trapezoidal MF_f is employed to transfer expert knowledge and engineering judgement into a comparison matrix (An et al., 2011; An et al., 2016). The qualitative descriptors and their corresponding trapezoidal MF_f numbers are described as shown in Table 5-1.

2. Compare risk hazard contributors and convert the pairwise comparison into fuzzy numbers. A total of N = (*n*-1) paired should be compared. For instance, for two risk hazards FH (Falls from height) and FO (Falling objects), if FH is more

absolutely important than FO, a trapezoidal fuzzy number of (8, 9, 9, 9) is assigned to FH, as shown in Table 5-1.

Table 5-1: Scale for relative importance used in the pairwise comparison matrix

Qualitative descriptors	Membership function
Equally important (EI)	(1,**1**,**1**,2)
Between equally important and weakly important (BE)	(1,**2**,**2**,3)
Weakly important (WI)	(2,**3**,**3**,4)
Between weakly important and strongly important (BW)	(3,**4**,**4**,5)
Strongly important (SI)	(4,**5**,**5**,6)
Between strongly important and very strongly important (BS)	(5,**6**,**6**,7)
Very strongly important (VS)	(6,**7**,**7**,8)
Between very strongly important and absolutely important (BV)	(7,**8**,**8**,9)
Absolutely important (AI)	(8,**9**,**9**,9)

3. Aggregate fuzzy numbers and construct the fuzzy pairwise synthesised matrix. The aggregated fuzzy numbers are employed to construct the pairwise synthesised matrix, as shown in Equation 5-5.

$$D = (X_{ij}) = \begin{matrix} & R_1 & R_2 & \cdots & R_n \\ \begin{matrix} R_1 \\ R_2 \\ \vdots \\ R_m \end{matrix} & \multicolumn{4}{l}{\begin{bmatrix} 1,1,1,1 & x_{12} & \cdots & x_{1n} \\ x_{21} & 1,1,1,1 & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{21} & \dots & 1,1,1,1 \end{bmatrix}} \end{matrix} \qquad \text{Eq. 5-5}$$

$i = 1, 2, \dots m; j = 1, 2, \dots, n$

$X_{ij} = \{a_{i,j}, b_{i,j}, c_{i,j}, d_{i,j}\}, X_{ji} = \{1/d_{i,j}, 1/c_{i,j}, 1/b_{i,j}, 1/a_{i,j}\}$

where X_{ij} indicates the aggregated trapezoidal fuzzy number representing the quantified judgement on R_i compared to R_j.

According to their definition, "A reciprocal multiplicative preference relation $M = (m_{i,j})$ is consistent if and only if $m_{i,j} \times m_{j,k} = m_{i,k}$, $i, j, k \in \{1,2,\ldots,n\}$ and $i \leq j \leq k$ " and "For a reciprocal multiplicative preference relation $M = (m_{i,j})$ $i \leq j \leq k$, the following statements are equivalent" (An et al., 2011; An et al., 2016). Therefore:

$$m_{i,j} \times m_{j,k} = m_{i,k}, \qquad i \leq j \leq k \qquad \text{Eq. 5-6}$$

$$m_{i,j} = m_{i,i+1} \times m_{i+1,i+2} \times \ldots, m_{j-1,j}, \quad i < j \qquad \text{Eq. 5-7}$$

For example, $m_{4,13} = \{a_{4,13}, b_{4,13}, c_{4,13}, d_{4,13}\}$ and $m_{13,4} = 1/m_{4,13} = \{1/d_{4,13}, 1/c_{4,13}, 1/b_{4,13}, 1/a_{4,13}\}$ can be obtained as

$$a_{4,13} = a_{4,5} \times a_{5,6} \times a_{6,7} \times a_{7,8} \times a_{8,9} \times a_{9,10} \times a_{10,11} \times a_{11,12} \times a_{12,13}$$

$$b_{4,13} = b_{4,5} \times b_{5,6} \times b_{6,7} \times b_{7,8} \times b_{8,9} \times b_{9,10} \times b_{10,11} \times b_{11,12} \times b_{12,13}$$

$$c_{4,13} = c_{4,5} \times c_{5,6} \times c_{6,7} \times c_{7,8} \times c_{8,9} \times c_{9,10} \times c_{10,11} \times c_{11,12} \times c_{12,13}$$

$$d_{4,13} = d_{4,5} \times d_{5,6} \times d_{6,7} \times d_{7,8} \times d_{8,9} \times d_{9,10} \times d_{10,11} \times d_{11,12} \times d_{12,13}$$

It should be noted that a consistent multiplicative preference method can be structured from a set of n-1 preference data within the interval $[1/v, v]$ (v>0). As a multiplicative preference relation decision matrix is not in the interval [1/9, 9], by taking logarithms, the above expressions can be obtained, as shown by An et al. (2016).

$$f(x_a) = x_a^{1/\log_9 v}, f(x_b) = x_b^{1/\log_9 v}, \qquad \text{Eq. 5-8}$$

$$f(x_c) = x_c^{1/\log_9 v}, \quad f(x_d) = x_d^{1/\log_9 v}$$

According to their definition, "A fuzzy matrix $M = (m_{i,j})$ is reciprocal if and only if $m_{i,j} = 1/m_{j,i}$" and "A fuzzy matrix $M = (m_{i,j})$ is consistent if and only if $m_{i,j} \times m_{j,k} = m_{i,k}$" (An et al., 2016).

4. Calculate fuzzy weight. The fuzzy weight can be determined by using the geometric mean method (Chen, 2013; An et al., 2016) and is defined as

$$X_i = \{a_i, b_i, c_i, d_i\} = \left\{ \begin{array}{c} \sqrt[n]{\prod_{j=1}^{n} a_{ij}}, \\ \sqrt[n]{\prod_{j=1}^{n} b_{ij}}, \\ \sqrt[n]{\prod_{j=1}^{n} c_{ij}}, \\ \sqrt[n]{\prod_{j=1}^{n} d_{ij}} \end{array} \right\} \quad \text{Eq. 5-9}$$

$$W_i = \{a_i, b_i, c_i, d_i\} = \left\{ \begin{array}{c} \frac{a_i}{\sum_{j=1}^{n} d_j}, \\ \frac{b_i}{\sum_{j=1}^{n} dc_j}, \\ \frac{c_i}{\sum_{j=1}^{n} b_j}, \\ \frac{d_i}{\sum_{j=1}^{n} a_j} \end{array} \right\} \quad \text{Eq. 5-10}$$

where W_i indicates the fuzzy weight of events

5. Compute the fuzzy weights of the alternatives. According to Equations (5-9) and (5-10), the fuzzy weight numbers are obtained using from the geometric mean method. Furthermore, the total weight factors (*WF*) can be calculated by using Equation (5-12)

$$W_i = \frac{ai + 2(bi + ci) + di}{6} \quad \text{Eq. 5-11}$$

$$WF = \frac{wi}{\sum_{j=1}^{n} wj} \quad \text{Eq.5-12}$$

5.4 Fuzzy Technique for Order Preference by Similarity to Ideal Solution (FTOPSIS)

FTOPSIS was developed based on traditional TOPSIS. This section outlines the development of TOPSIS.

5.4.1 Traditional TOPSIS

The TOPSIS method was originally suggested by Hwang et al. (1981) for MCDM problems (Yoon and Hwang et al., 1980; KarimiAzari et al., 2011; Tamosaitiene et al., 2013; Jato-Espino et al., 2014). This technique is a very helpful concept for coping with situations which are too complex to be calculated (Zavadskas et al., 2010). The main idea of this technique is regarding the chosen alternative that should have the shortest and farthest distances from the positive ideal and negative ideal solutions respectively (Tan et al, 2010; Chen, 2013). A wide variety of studies on TOPSIS methods can be found in Chapter 2. However, the traditional formulation of the TOPSIS method, human judgements in the decision-making process, is represented with crisp numbers, non-obtainable and incomplete information. The FTOPSIS will be outlined in the following section.

5.4.2 Fuzzy Technique for Order Preference by Similarity to Ideal Solution (FTOPSIS)

The FTOPSIS method is an MCDM method which has been employed to solve the problems under the fuzzy environment. It can be used to address both quantitative and qualitative risk data and information in the classic TOPSIS.

The procedure of FTOPSIS is similar to the classic one and can be represented in a chain of calculation steps (Zavadskas et al., 2010; Tamosaitiene et al., 2013; Taylan et al., 2014):

1. Construct the normalised fuzzy decision matrix, after obtaining the initial decision matrix. A fuzzy MCDM can be determined in the matrix format as (Taylan et al., 2014):

$$D = (x_{ij}) = \begin{array}{c} \\ A_1 \\ A_2 \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{matrix} C_1 & C_2 & \cdots & C_n \end{matrix} \\ \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{n2} & \cdots & x_{mn} \end{bmatrix} \end{array} \qquad \text{Eq. 5-13}$$

$$i = 1, 2, \ldots m; j = 1, 2, \ldots, n$$

The element x_{ij} of the matrix indicates the rating of performance of the ith alternative project. The normalised fuzzy numbers decision matrix was calculated by (Tan et al., 2010; Taylan et al., 2014)

$$R_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m} x_{ij}^2}} \qquad i = 1, 2, \ldots m; j = 1, 2, \ldots, n \qquad \text{Eq. 5-14}$$

2. Determination of the weighted and normalised matrix of decision. The weighted and normalised value v_{ij} is determined as follows:

$$v_{ij} = R_{ij} \times WF_j \qquad i = 1, 2, ..., m ; j = 1, 2, ..., n \qquad \text{Eq. 5-15}$$

   where WF_j is the weight of the jth attribute.

3. Obtain the fuzzy positive ideal solution (A^+) and the fuzzy negative ideal solution (A^-) (Tan et al., 2010; KarimiAzari et al., 2011; Chen, 2013; Taylan et al., 2014)

$A^{+} = (v_1^{+}\max, v_2^{+}\max, v_3^{+}\max,\ldots, v_n^{+}\max)$ Eq. 5-16

$A^{-} = (v_1^{-}\min, v_2^{-}\min, v_3^{-}\min,\ldots, v_n^{-}\min)$ Eq. 5-17

where $v_j^{+} = \max\ \{v_{ij}\}$ i =1, 2,..., m ; j = 1, 2, ..., n

where $v_j^{-} = \min\ \{v_{ij}\}$ i =1, 2,..., m ; j = 1, 2, ..., n

4. Compute the separation process by the m-dimensional Euclidean distance. The separation process of each option from the fuzzy positive ideal solution and the fuzzy negative ideal solution, respectively was calculated (Zavadskas et al., 2010) as

$$d_i^{+} = \sqrt{\sum_{j=1}^{m}(v_{ij} - v_j^{+})^2} \quad i = 1, 2, \ldots m$$ Eq. 5-18

$$d_i^{-} = \sqrt{\sum_{j=1}^{m}(v_{ij} - v_j^{-})^2} \quad i = 1, 2, \ldots m$$ Eq. 5-19

5. Compute the fuzzy closeness coefficient to the ideal solution. The fuzzy closeness coefficient of each alternative is calculated by (Tan et al., 2010; KarimiAzari et al., 2011)

$$CC_i^{*} = \frac{d_i^{-}}{d_i^{+} + d_i^{-}} \qquad i = 1, 2, \ldots m$$ Eq. 5-20

5.5 Summary

FRT, AHP, FAHP, MFAHP, TOPSIS and FTOPSIS have been reviewed in this chapter. The FRT based on the conceptual basis of fuzzy logic and the classical fuzzy set containing the membership function, fuzzification process, fuzzy inference and defuzzification process are outlined. It provides a suitable method to handle imprecision and ambiguity in qualitative data and information in a uniform manner. Furthermore, the AHP, FAHP and MFAHP employed to create appropriate weightings of the criteria have been presented. The AHP has a particular application in the group decision-making method which is usually used in many fields around the world, especially in making comparisons. The MFAHP was introduced to deal with a huge amount of judgemental information, as it reduces the uncertainty associated with experts' judgements. Moreover, the overall approach of FTOPSIS based on the traditional TOPSIS was introduced, in which a final ranking for evaluating the importance of safety risks can be obtained for building construction projects. The developed construction safety risk management model will be presented in Chapter 6.

CHAPTER SIX

DEVELOPMENT OF SAFETY RISK MANAGEMENT APPROACH

6.1 Introduction

This chapter presents the developed safety risk management model. Section 6.2 introduces a third safety risk assessment parameter, probability of consequence. The proposed construction safety risk management model, which includes the steps of safety hazard identification and risk data collection, safety risk criteria calculation, safety risk estimation, safety risk ranking, safety risk control and mitigation and safety risk monitoring, is discussed in section 6.3. Section 6.4 presents a case example showing safety risk management in building construction projects. At the end of this chapter, some features of the developed safety risk management model are discussed. This chapter incorporates content from a conference publication jointly by the author (Sansakorn and An, 2015).

6.2 Suggestion for the Third Parameter (Sansakorn and An, 2015)

Two fundamental safety risk parameters, probability of occurrence (PO) and severity of consequence (SC), are commonly used to assess risk magnitude (RM) in safety management of a construction project. PO represents the likelihood that an event will happen. SC defines the number of minor injuries, major injuries and fatalities resulting from the occurrence of a specific event. The magnitude of a specific risk also depends highly upon the probability that the accident will occur. These two parameters do not take into account the probability of the consequence caused in the consideration of the project safety risk assessment process to obtain accurate and the reliable results. Therefore, a third parameter, probability of consequence (PC), is proposed. PC indicates the likelihood of the occurrence of an accident if an event becomes a reality to assess such a safety risk associated with the construction project's effectiveness and efficiency.

6.3 Proposed Construction Safety Risk Management Model (Sansakorn and An, 2015)

The architecture of the proposed construction safety risk management model is shown in Figure 6-1, which includes the development of the qualitative descriptors representing risk inputs, i.e. probability of occurrence (PO), severity of consequence (SC), and probability of consequence (PC), and risk outputs, i.e. risk magnitude (RM). The proposed model consists of six steps: risk data collection and hazard identification, risk criteria calculation, risk estimation, risk ranking, risk control and mitigation, and risk monitoring. The details of the proposed safety risk management model are described in the following sections.

6.3.1 Step 1: Risk Data Information Collection and Hazard Identification

6.3.1.1 Establishing a safety risk management team (Sansakorn and An, 2015)

To identify safety hazards associated with a construction project, a safety risk management team composed of people from different disciplines/backgrounds needs to be established. The members of a safety risk management team must be carefully selected. The selected experts should have essential experience and a high degree of knowledge of the construction activities (Zeng et al., 2007). The safety risk management team should include experts, for example, site construction managers, project managers, site engineers, and safety officers (An et al., 2011). The safety risk management team will undertake the review of safety hazard identification and risk data.

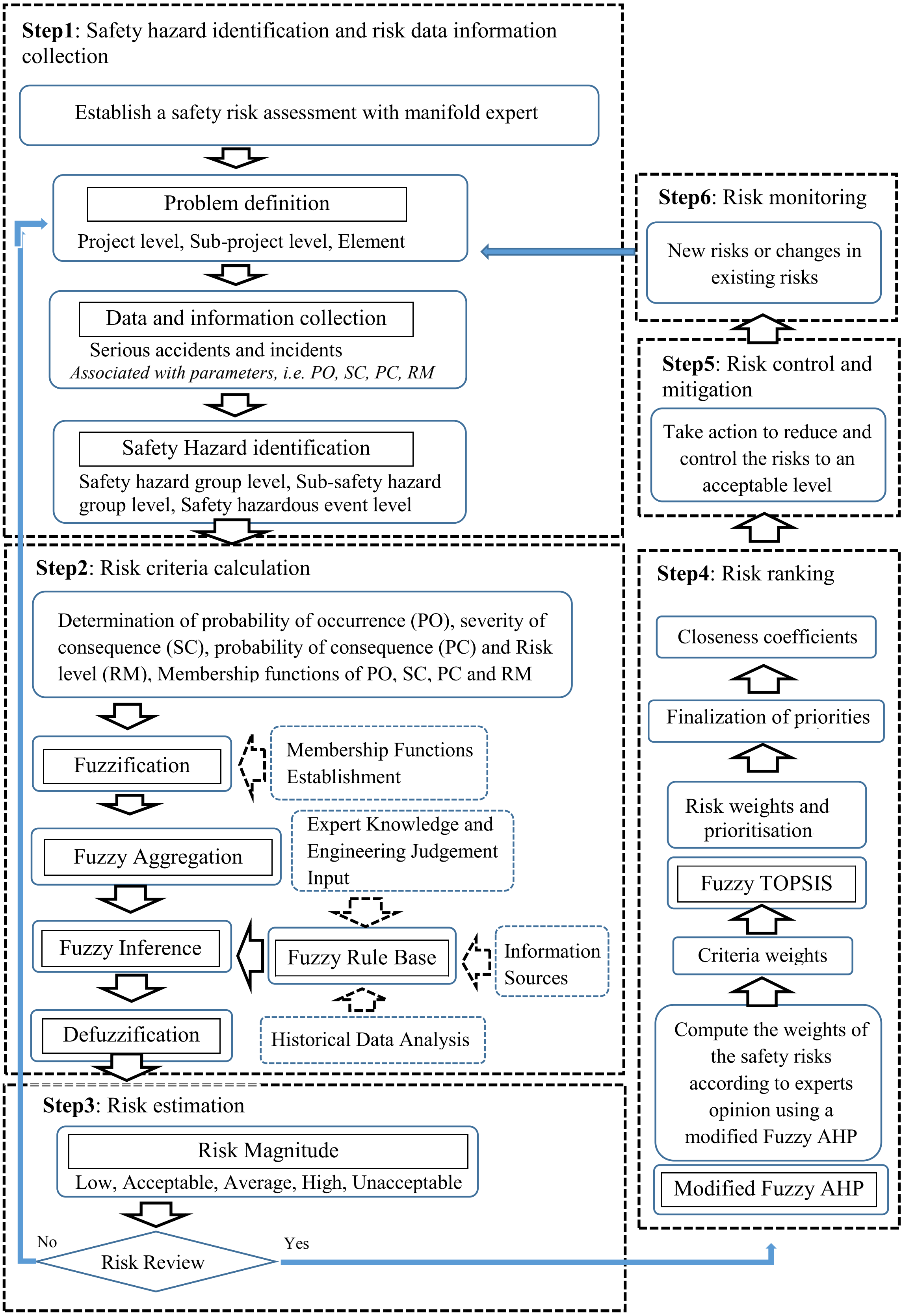


Fig. 1 Construction safety risk management modeling

Figure 6-1: Construction safety risk management model (Adopted from Sansakorn and An, 2015)

6.3.1.2 Allocation of experts' contribution factors

A contribution factor is allocated to each member of the safety risk management team based on their individual skills, knowledge, experience, and expertise. Scores are employed to compute the contribution factors. All the weight factors must add up to 1 ($C_n = E_1+E_2+E_3+\ldots+E_n = 1$), where E_n is assigned as a contribution factor of each expert and assumes that there are n experts in the safety risk management team. When the circumstances have changed, however, it is necessary to review the contribution factors.

6.3.1.3 Problem definition (Sansakorn and An, 2015)

Safety risk management starts with the problem definition, which involves identifying the specific safety requirements at different levels of a project, e.g. at the project level, sub-project levels, and element levels of a project. The requirements may include safety regulations and safety rules developed by the HSE and the company's policy. For example, a construction building project can be divided into specific activities in the construction process, for which risk hazard identification can be carried out based on the activities identified, as shown in Figure 6-2. Level 1 shows that the construction building project can be categorised into M sub-projects based on the types of safety risks, e.g. sub-project 1, sub-project 2… and sub-project M at level 2. Each sub-project can be broken down into activities at level 3. At level 4, each activity can also be broken down into all possible safety risk hazards, for example, risk hazard 1 is falls from height, risk hazard 2 is falling objects, risk hazard 3 is manual handling, risk hazard 4 is equipment, machinery and tools and risk hazard 5 is electricity.

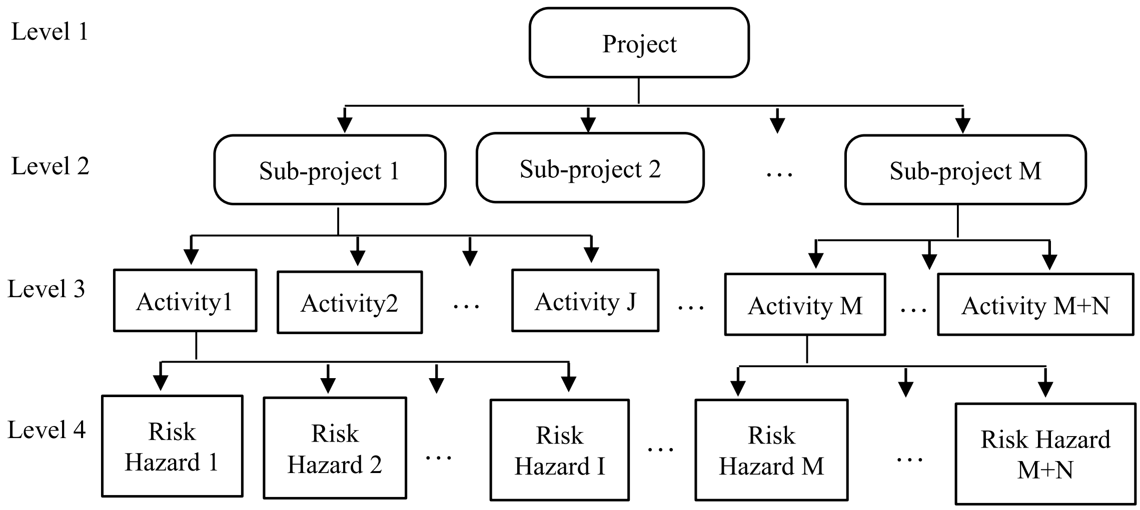


Figure 6-2: The hierarchical structure of problem definition for construction risk projects

6.3.1.4 Data and information collection (Sansakorn and An, 2015)

Once the problem definition is completed, the safety risk assessment moves from the problem definition to the data collection. The data can be collected from previous similar projects, reports and databases. In many cases, however, if the statistical record does not exist, expert judgement needs to be applied. Moreover, the data collection will be expressed as qualitative descriptors and associated with parameters, i.e. PO, SC and PC.

6.3.1.5 Safety hazard identification (Sansakorn and An, 2015)

All the potential safety hazards associated with a building construction project need to be identified and classified into different categories at different levels. The process of hazard identification must involve an investigation into all the potential sources of project construction risk and their consequences. Many of the tools and techniques for hazard identification, including checklists, 'what if?' analysis, the brainstorming approach, FMEA, HAZOP study, concept hazard analysis (CHA), preliminary hazard analysis (PHA), job hazard analysis (JHA), and Inherent hazard analysis (IHA) (Glossop et al., 2000; Rozenfeld, 2010; An et al., 2011; Pinto et al., 2011; Liu and Tsai, 2012), are widely used in the construction industry, and they can be applied to identify the hazards of a project. The information gained from hazard identification will be used in the risk analysis.

Checklists are utilised to identify, review, and correct any conditions or tasks, potential hazards that may arise from direct or indirect exposure to a construction project or are lists of known hazards or hazard causes that have been derived from past experience. This technique is a simplistic tool that can be employed by inexperienced practitioners (Glossop et al., 2000; Liu and Tsai, 2012) and can be carried out by a small, multidisciplinary group composed of experienced people. Therefore, checklists are a valuable hazard identification tool; however, it is not easy to develop a well-designed checklist (Pinto et al., 2011). In other operating conditions, existing checklists may not be used as the sole tool in the hazard identification process, since they may not cover all types of hazard, particularly facility-specific hazards.

'What if?' analysis is one of the most commonly used techniques for identifying potential hazards. It is a structured brainstorming approach for determining specific what-if questions about the construction process being reviewed. This method is conducted by a facilitator who designates the construction process scope. This technique is easy to use and has been effectively applied to various projects (Glossop et al., 2000).

Brainstorming, the most common approach used in risk identification (Lyons and Skitmore, 2004), is an unrestricted but facilitated discussion within a group of experts. A facilitator prepares prompts or issues ahead of the group session and then encourages imaginative thinking and discussion among group members during the session. This technique is complementary to systematic functional hazard identification (An et al., 2011). The brainstorming method can reveal hazards not identified in the systematic approach.

PHA is a qualitative technique which is used to identify all potential hazards and accidental events that may lead to an accident (Pinto et al., 2011; Liu and Tsai, 2012). This technique is used as an early means of hazard identification during the design and development of the process. It is often used to follow-up on the hazards that have been identified during CHA (Glossop et al., 2000). In fact, PHA consists of drawing a table by matching a danger with one or more unwanted events and potential causes at the system and sub-system level. The last column will list the requirements in respect of each of the potential causes identified. An example of a PHA is shown in Table 6-1.

Table 6-1: An example of PHA (Source: Shewring, 2011)

Hazard Description	Potential Cause	Possible Consequences	Possible Controlling Measures
1. Collision between construction trucks	Excessive speed, failure to follow road safety and vehicle regulation.	Injury due to crash	Speed limit on roads reduced from 40 kph to 15 kph
2. Vehicle striking 132 kV electric lines	Boom left up on crane while moving beneath.	Electrocution	Using resistant equipment designed to reduce the possibility of direct contact with the overhead power line

FMEA is used to identify potential hazards associated with a process by investigating the failure modes for each process item. This technique has difficulty in identifying hazards that require the failure of more than one process item due to the complex interaction of the failures (Glossop et al., 2000). An example of FMEA is shown in Table 6-2 (Nielsen, 2002).

Table 6-2: An example of FMEA (Source: Nielsen, 2002)

Process function	Potential failure mode	Potential effect(s) of failure	Current process controls
Leakage in roofing material	Mechanical damage	Seen as dripping or water flow in the building during and after rain. Finding location of damage can be very difficult	No normal traffic on the roofing material. Remove all waste material from roofs. Inspect roof
	Montage error	The roof leaks shortly after construction. Seen as dripping or water flow in the building during and after rain. Finding the location of damage can be very difficult.	Control system for workmanship. The contactor must repair the damage.
	Ageing of material	The material cracks from frost damage or temperature variation.	Use materials tested for aging in a climate like the one on site. Inspect roof and look for cracks or other damage.

JHA is a systematic way to identify hazards associated with a specific task or operation. It is useful for communicating and controlling known hazards in the workplace. Also called job safety analysis, this technique is a way for the employers and employees to document hazards and note the steps necessary to reduce or eliminate the risk when performing a particular task (Rozenfeld et. al., 2010). An example of JHA is shown in Table 6-3 (Reese and Eidson, 2006).

Table 6-3: An example of a JHA: replacing tyre on pickup truck (Source: Reese and Eidson, 2006)

Steps	Hazard description	Hazard controls
1) Prepare tools to change tyre.	1.1 Struck by a pickup truck 1.2 Slip and fall to same level 1.3 Exposure to cold, frostbite 1.4 Overexertion removing spare tyre from carrier	1.1 Engine must be switched off 1.2 Observe area. Remove tripping or stumbling hazards or move vehicle to better location 1.3 Wear PPE such as gloves and appropriate clothing 1.4 Follow safety manual
2) Raise truck	2.1 Struck by a pickup truck	2.1 Place truck in park and engage parking brake. Raise truck using jack until flat tyre is totally off the ground
	2.2 Struck by jack	2.2 Follow jacking procedure carefully
	2.3 Contact with hot exhaust	2.3 Exhaust system may be very hot (do not touch)
	2.4 Overexertion using jack	2.4 Use jack as described in safety manual
3) Change tyre	3.1 Caught between tyre and ground	3.1 Check jack stability before any work is performed on the raised truck
	3.2 Overexertion lifting tyre off	3.2 Use proper lifting techniques
	3.3 Contact with hot hub wheel	3.3 Wear gloves when removing tyre

A HAZOP study is a systematic and structured approach using parameter and deviation guidewords that is very useful in identifying hazards for a specific design phase. The technique relies on a very detailed system description being available and usually involves breaking down the system into well-defined sub-systems and functional or process flows between sub-systems. Each element of the system is then subjected to discussion within a multidisciplinary group of experts against the various combinations of the guidewords and deviations (Glossop et al., 2000). In a complex construction project such as a hospital, it may be helpful for design engineers (Lingard and Rowlinson, 2005). An example of HAZOP is shown in Table 6-4.

Table 6-4: An example of a HAZOP study (Source: García-Serna, 2007)

Guideword	Deviation	Causes	Consequences	Safety guards	Recommendations
More	Flow	1. Pressure in tank increases	1.1. Pressure in the line increases up to control valve	1.1.1. Lines are designed to support that pressure. No consequences for safety	
		2. Control system fails	2.1. More vent gas to scrubber. Scrubber pressure increases. Scrubber cannot clear all the vented gas. Gases containing methyl isocyanate (MIC) are vented into the atmosphere. Gases containing MIC are vented into the flare system	2.1.1. Pressure safety valves connected to the flare 2.1.2. Bypass line direct to the flare. Rupture disk	
Less	Flow	1. Nitrogen valve closes	1.1. Low pressure in vessel during emptying	1.1.1. Possibility of backward pressurisation through the scrubber line	1.1.1.1. Install a low-pressure interlock that stops the feed pump.

CHA consists of a literature review of previous incidents, enabling identification of areas of the process of specific concern. It is performed during the concept and early design stages and requires the process flow diagram, with any main add-on safety systems (Glossop et al., 2000). An example of CHA is shown in Table 6-5 (Rasmussen and Whetton, 1997).

Table 6-5: An example of CHA (Source: Rasmussen and Whetton, 1997)

Description	Keyword	Main variance	Consequence	Mitigation
Contain process fluids	NOT	Flammable gas released into atmosphere	Possible fire and explosion	Maintain standards of construction through regular inspections and preventive maintenance.
Avoid release of process materials.	NOT	Release flammable materials to flare, where they are burned	Unnecessary loss of energy, bright lights at night, etc.	Consider gas detectors and water sprays at critical locations
Ensure safe effluent disposal	NOT	Failure to ensure safe disposal of effluent which may be toxic		Consider use of off-spec gas as fuel
	FLAMMABLES	Failure to ensure safe disposal of liquid draining from D-102, which will contain dissolved hydrogen and methane	Hydrogen and/or methane will be liberated into the sewers, where it may be transported considerable distances before reaching a source of ignition	Install gas detectors and forced ventilation system with safe disposal of liberated gases

6.3.2 Step 2: Risk Criteria Calculation (Sansakorn and An, 2015)

This step is to calculate the risk criteria, which consists of eight principal components: determining the risk criteria, determining fuzzy membership functions, inputting PO, SC and PC, converting input into standardised trapezoidal fuzzy number, fuzzy aggregation, fuzzy inference, fuzzy rule base, and defuzzification as described below.

6.3.2.1 Determining the risk criteria (Sansakorn and An, 2015)

The three fundamental risk parameters are used to assess the risk magnitude of the safety construction industry, i.e., PO, SC and PC. The safety risk management team needs to discuss and select a set of criteria for safety risk assessment. Risk criteria are standards, which define the scope of the risk parameters, PO, SC, and PC.

PO refers to the number of times an event occurs or the failure frequencies in a certain time period, which may estimate PO as "*Very unlikely*", "*Unlikely*", "*Fairly unlikely*", "*Likely*", and "*Very likely*", as shown in Table 6-6.

Table 6-6: Definitions of qualitative descriptors of PO

Qualitative descriptors	Description	Range
Very unlikely	Failure is unlikely but possible during lifetime	0.0-1.0
Unlikely	Likely to happen once during lifetime	0.5-2.0
Fairly unlikely	Between unlikely and likely	1.5-3.5
Likely	Occasional failure	3.0-4.5
Very likely	Failure is almost unavoidable	4.0-5.0

Source: Sansakorn and An, 2015

SC refers to the number of minor injuries, major injuries and fatalities resulting from the occurrence of a specific event. Five linguistic variables, "*Negligible*", "*Minor*", "*Moderate*", "*Major*", and "*Catastrophic*", are used to describe consequence severity to estimate SC, as shown in Table 6-7.

Table 6-7: Definitions of qualitative descriptors of SC

Qualitative descriptors	Description	Range
Negligible	No injury	0.0-1.0
Minor	Minor injuries and/or < 3 days off work	0.5-2.0
Moderate	Multiple injuries and/or between 3 days and 1 month off work	1.5-3.5
Major	Severe injuries and/or >1 month off work	3.0-4.5
Catastrophic	Fatality and/or large number of fatal injuries	4.0-5.0

Source: Sansakorn and An, 2015

PC is a new parameter which refers to the occurrence likelihood of the accident if an event becomes a reality. Six linguistic variables are used in this research to describe PC, "*Highly unlikely*", "*Unlikely*", "*Reasonably unlikely*", "*Likely*", "*Reasonably likely*", and "*Highly likely*", as shown in Table 6-8.

Table 6-8: Definitions of qualitative descriptors of PC

Qualitative descriptors	Description	Range
Highly unlikely	The probability of accident occurrence is highly unlikely	0.0-1.0
Unlikely	The probability of accident occurrence is unlikely but the failure event could occur	0.5-2.0
Reasonably unlikely	The probability of accident occurrence is between unlikely and likely	1.5-3.0
Likely	The probability of accident occurrence is likely	2.5-4.5
Reasonably likely	The probability of accident occurrence is between likely and highly likely	4.0-5.5
Highly likely	The probability of accident occurrence is very likely	5.0-6.0

The five levels of *RM* in terms of linguistic variables are defined as "*Low*", "*Acceptable*", "*Average*", "*High*", and "*Unacceptable*". Their definitions are generally similar to those in the occupational health and safety management regulations published by the HSE as shown in Table 6-9.

Table 6-9: Definitions of qualitative descriptors of RM

Qualitative descriptors	Description	Range
Low	Risk is low or insignificant and can be readily controlled	0.0-1.0
Acceptable	Risk is acceptable	0.5-2.0
Average	Risk is medium	1.5-3.5
High	Risk is high; however, risk control should be undertaken if it is reasonably practicable to so	3.0-4.5
Unacceptable	Risk is unacceptable; proper action must be taken to eliminate or reduce the risk	4.0-5.0

Source: Sansakorn and An, 2015

6.3.2.2 Determine fuzzy membership functions (MF_f) (Sansakorn and An, 2015)

In the literature, linguistic variables are described by different types of fuzzy membership functions according to the situation in the interested area, including triangular, trapezoidal, generalised bell- shaped, and S-shaped functions (Zeng et al., 2007). However, trapezoidal and triangular membership functions are the most frequently used in construction project risk assessment. The selection of the form of MF_f by the safety risk management team is generated by the usefulness of the linguistic groups identified in the knowledge acquisition and consists of a set of overlapping curves. Figures 6-3-6-6 show the MF_f of PO, SC, PC, and RM.

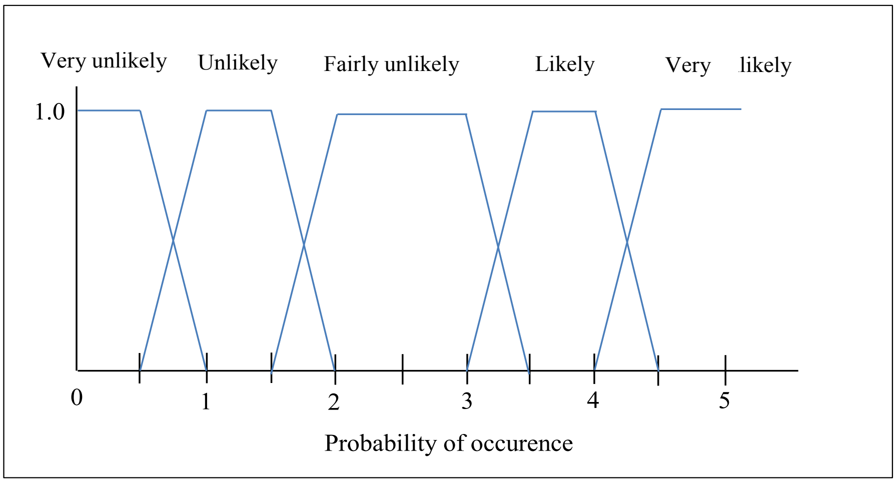


Figure 6-3: Fuzzy probability of occurrence definition

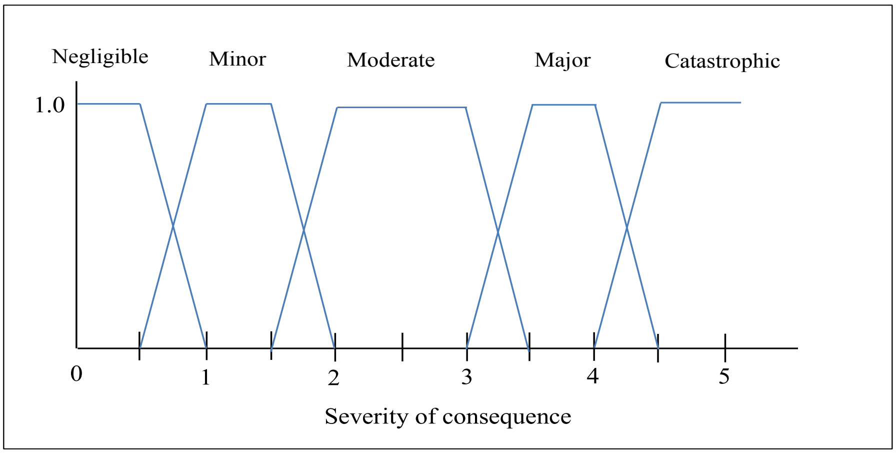


Figure 6-4: Fuzzy severity of consequence definition

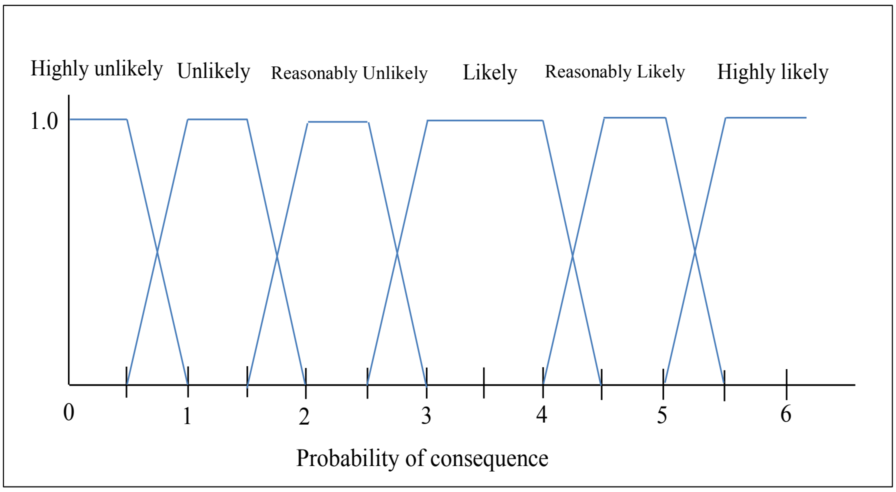


Figure 6-5: Fuzzy probability of consequence definition

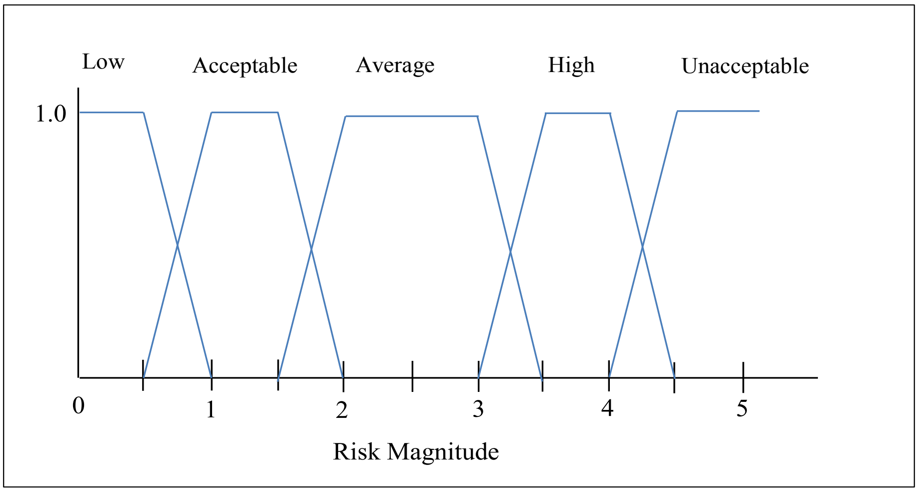


Figure 6-6: Fuzzy risk magnitude definition

6.3.2.3 Input PO, SC and PC (Sansakorn and An, 2015)

Input data can usually be derived from several sources, for example historical data, experts' judgements, and experiences. The data format of the inputs can be a range of numbers, e.g. (3, 5), a linguistic term, e.g. "Unlikely", a numerical value, e.g. "5", triangular fuzzy numbers, e.g. (1, 2, 3), or trapezoidal fuzzy numbers, e.g. (1, 2, 3, 4) (see Table 6-10).

Table 6-10: Experts' judgement and corresponding standard trapezoidal fuzzy number (STFN)

Input type	Description	Input values	Example	STFN
A numerical value	….is *a*	*a*	2	(2,2,2,2)
A range of numbers	….is between *a* and *b*	(*a*, *b*)	(2,3)	(2,2,3,3)
A linguistic term #1	….is High	High	High	(4,4.5,5,6)
A linguistic term #2	….is about *c*	About *c*	About 4	(3,4,4,5)
A triangular fuzzy number	….is between *a* and *c* and most likely to be *b*	(*a*, *b* , *c*)	(2,3,4)	(2,3,3,4)
A trapezoidal fuzzy number	….is between *a* and *d* and most likely to be *b* and *d*	(*a*, *b*, *c*, *d*)	(2,3,4,5)	(2,3,4,5)

6.3.2.4 Convert input into Standardised trapezoidal fuzzy number (STFN) (Sansakorn and An, 2015)

A triangular membership function is a function of $\mu_A(x)$ that depends on the scalar parameter *a* as a lower limit, *d* as an upper limit, and $a< b< c< d$ Figure 6-7 presents the diagram and formula of trapezoidal membership functions. However, if $b=c$, it is triangular membership functions.

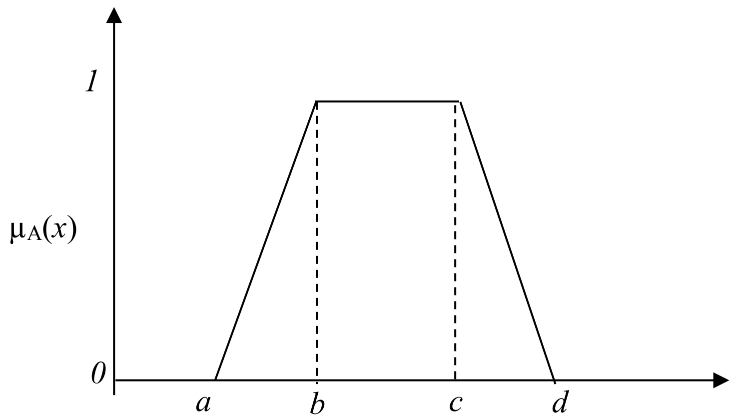


Figure 6-7: Illustration of trapezoidal member functions (MF_f)

The STFN is employed to convert the judgement of experts into a universal format for the composition of group preferences. An STFN can be defined as X= (*a*, *b*, *c*, *d*), with its membership function indicating the degree of preference (Zeng et al., 2007; An et al., 2011), which is defined as

$$m_A(x) = \begin{cases} 0, x \le a \\ (x - a)/(b - a), x \in (a,b) \\ 1, x \in (b,c) \\ (d - x)/d - c), x \in (c,d) \\ 0, x \ge d \end{cases} \qquad \text{Eq. 6-1}$$

where *A* set of real numbers (*a*, *b*, *c*, *d*) with the relationship's satisfaction $a \le b \le c \le d$ determines the *x* coordinate of the four points of a trapezoidal MF_f.

6.3.2.5 Aggregated STFN of PO, PC and SC (Sansakorn and An, 2015)

The fuzzy aggregation of STFN scores can be carried out by applying the fuzzy weighted trapezoidal averaging operator, which is defined by

Fuzzy aggregated score (F_{agg}) = $STFN_{1i} \times c_1 + STFN_{2i} \times c_2 \ldots + STFN_{ni} \times c_n$ Eq. 6-2

where F_{agg} is the fuzzy aggregated score, $STFN_{1i}$, $STFN_{2i}$,…, $STFN_{ni}$ are the STFN scores of parameter i measured by experts respectively, and c_n are contribution factors allocated to experts, for example, c_1 assigned to $Expert_1$, and $c_1+c_2+\ldots, c_n = 1$.

It should be noted that if some experts provide zero scales (An et al., 2011), the aggregation of STFN scores is defined as

Fuzzy aggregated score ($F_{agg'}$) = $$\frac{STFN_{1i} \times c_1 + STFN_{2i} \times c_2 \ldots + STFN_{ni} \times c_n}{1 - \sum cn}$$ Eq. 6-3

where $F_{agg'}$ is the aggregated fuzzy scale and c_n is the contribution of experts who provide zero scales.

6.3.2.6 Calculation of fuzzy values (STFN) (Sansakorn and An, 2015)

Assume A_{PO}, A_{SC} and A_{PC} are three STFN of PO, SC and PC of a hazardous event respectively. A_{PO}, A_{SC} and A_{PC} are defined as

$$A_{PO} = \{(u, \mu A_{PO}(u) | u \in U = [0, u], \mu A_{PO}(u) \epsilon [0,1]\}$$ Eq. 6-4

$$A_{SC} = \{(v, \mu A_{SC}(v) | v \in V = [0, v], \mu A_{SC}(v) \epsilon [0,1]\}$$ Eq. 6-5

$$A_{PC} = \{(w, \mu A_{PC}(w) | w \in W = [0, w], \mu A_{PC}(w) \epsilon [0,1]\}$$ Eq. 6-6

where μA_{PO}, μA_{SC}, and μA_{PC} are trapezoidal MF_f of A_{PO}, A_{SC}, and A_{PC} and u, v and w are input variables in the universe of discourse U, V and W of PO, SC and PC respectively.

6.3.2.7 Fuzzy reasoning evaluation (Sansakorn and An, 2015)

The Mamdani method as stated in Section 5.2.6 of Chapter 5, is employed to develop a fuzzy reasoning process where rules are relevant to the current situations of the project to calculate the fuzzy output. The fuzzy rule base comprises the following fuzzy if-then rules (Zeng et al., 2007; Majumder et al., 2013):

R_i: If u is Q^i_{PO} and v is Q^i_{SC} and w is Q^i_{PC}, then x is Q^i_{RM} Eq. 6-7

where $i = 1,2,3\ldots,n$ and u, v, w, and x are variables in the universe of discourse U, V, W, and X of PO, SC, PC, and RM, and Q^i_{PO}, Q^i_{SC}, Q^i_{PC}, and Q^i_{RM} are qualitative descriptors of PO, SC, PC, and RM respectively.

In this study, the rule base consists of 150 if-then rules. For a three-by-one system, the deputation develops the shape of a $PO \times SC \times PC$ cube as shown in Figure 6-8. It can be seen that each sliced fuzzy cubic rule consists of 25 rules with a particular PC descriptor, such as 1= Highly unlikely, 2 = Unlikely, 3 = Reasonably unlikely, 4 = Likely, 5 = Reasonably likely and 6 = Highly likely.

The firing strength of α_i of the ith rule with input fuzzy sets A_{PO}, A_{SC}, and A_{PC} is calculated using fuzzy intersection operation as

$$\alpha_i = \min[\max\left(\mu A^i{}_{PO}(u) \cap \mu Q^i{}_{PO}(u)\right), \max\left(\mu A^i{}_{SC}(v) \cap \mu Q^i{}_{SC}(v)\right), \max(\mu A^i{}_{PC}(w) \cap \mu Q^i{}_{PC}(w)] \quad \text{Eq. 6-8}$$

where $\mu A^i{}_{PO}(u)$, $\mu A^i{}_{SC}(v)$ and $\mu A^i{}_{PC}(w)$ are the MF_f of fuzzy sets A_{PO}, A_{SC} and A_{PC}, respectively.

The control output of fired rule R_i is obtained by

$$\mu Q^{i}{}_{RM'}(x) = \alpha_i \cap \mu Q^{i}{}_{RM} \qquad \text{Eq. 6-9}$$

where α_i is the firing strength of rule R_i, and $\mu Q^{u}{}_{ire}$ is the membership functions of fuzzy set A_{PO}, A_{SC} and A_{PC} respectively.

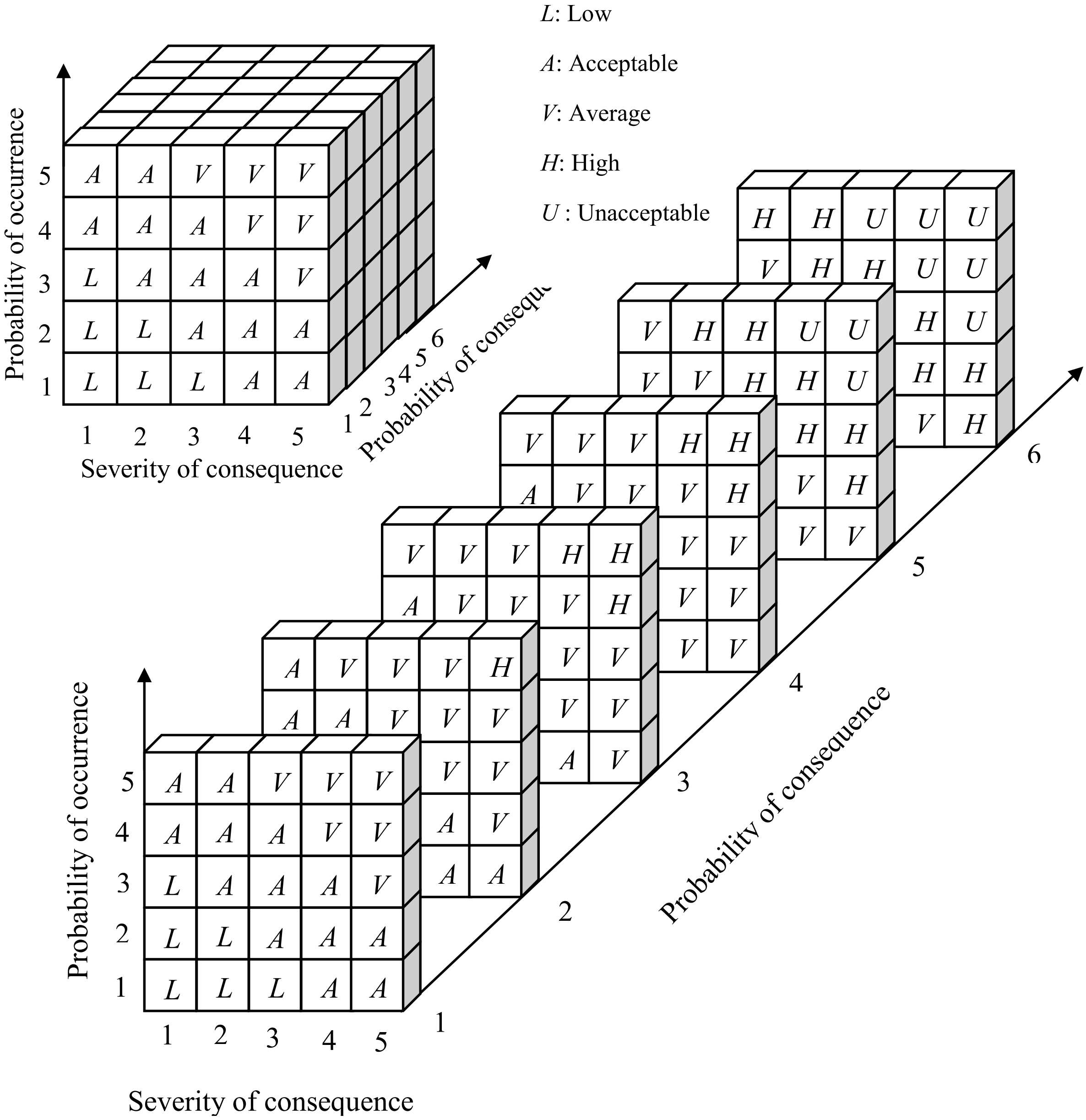


Figure 6-8: Fuzzy cubic rules and sliced fuzzy cubic rule deputations

(See further details in Figure 6-12)

The maximum operator can be used to calculate the total relation by (An et al., 2011)

$$\mu {Q^i}_{RM'}(x) = \max\{\min(\mu {Q^i}_{RM1}, \mu {Q^i}_{RM2}, \ldots, \mu {Q^i}_{RMn})\} \quad \text{Eq. 6-10}$$

$\mu {Q^i}_{RM'}(x)$ is the output fuzzy membership function after aggregation.

6.3.2.8 Defuzzification (Sansakorn and An, 2015)

The defuzzifier is defined as the output of the fuzzy inference engine to crisp point. Conceptually, the task of this step is an important procedure to convert the aggregated result into a crisp number. The centre average method is most commonly employed for defuzzification (Zeng et al., 2007; An et al., 2011). Assume the output of fuzzy inference engine is obtained as:

$$\mu Rl = \{(x, \mu RM(x)) | x \in X, \mu Rl(x) \in [0,1]\} \quad \text{Eq. 6-11}$$

and RM can be calculated as

$$\text{RM} = \frac{\sum_{i=1}^{n} c_i \mu RM(c_i)}{\sum_{i=1}^{n} \mu RM(c_i)} \quad \text{Eq. 6-12}$$

where $i = 1,2,3, \ldots, n$, c_i denotes the centre of fuzzy term set i of RM, and $\mu RM(c_i)$ denote the membership function of the fuzzy term set of RM.

It should be noted that the fuzzy weight factors of safety risk groups are obtained based on the MFAHP as mentioned in chapter 5. The overall $RM_{Project}$ of the construction safety project is defined by

$$RM_{project} = \sum_{i=1}^{n} RM_{sub-project} \times WF_{sub-project} \qquad i = 1, 2, 3\ldots, n \quad \text{Eq. 6-13}$$

where *RM* is Risk Magnitude and *WF* is fuzzy weight factor, Similarly, the $RM_{sub-project}$ of a construction safety project can be obtained by

$$RM_{sub-project} = \sum_{i=1}^{n} RM_{hazard-group} \times WF_{hazard-group} \quad i = 1,2,3\ldots, n \qquad \text{Eq. 6-14}$$

6.3.3 Step 3: Establishment of Risk Estimation (Sansakorn and An, 2015)

The outcomes of risk assessment are represented as the risk magnitude, such as low, acceptable, average, high and unacceptable risk, which can be used in the decision-making of safety officers, risk analysts, engineers and project managers. However, the results need to be reviewed by experts and risk analysts in the safety risk management group.

6.3.4 Step 4: Risk Ranking

The purpose of risk ranking is to identify and rank the safety risks in construction projects, based on the outcomes of risk assessment to address all the safety risks on all construction project sites effectively based on limited resources. To overcome this problem properly, the risk level of each project must be assessed and prioritised, so that an appropriate level of effort can be applied to manage those projects safely. Specifically, resources will be directed to manage construction sites with a higher safety risk ranking. The proposed methodology involves ranking all the safety risks using FTOPSIS and FAHP calculations in a merged listing with all identified and assessed safety risks ranked from safety risk with the highest importance to the safety risk with the lowest importance.

6.3.5 Step 5: Controlling and Mitigating Risk Hazards (Sansakorn and An, 2015)

The best way to control a risk hazard is to eliminate the hazard. If this is not reasonably practicable, apply the hierarchy of control to reduce the risk. A combination of these controls may be used. Administration and PPE must be implemented if the risk still exists after the other control measures have been implemented (Hughes and Ferrett, 2012).

Risk hazard mitigation measures must be applied by reducing the probability of occurrence or controlling the possible consequence if a hazardous event has been identified and analysed with as having high risk level.

6.3.6 Step 6: Monitoring Risk Hazards

Monitoring is a vital part of construction safety risk management (Carr and Tah, 2001). It is important to determine whether the risk assessment was complete and accurate. It is also essential to ensure that changes in the workplace have not introduced new hazards or changed hazards that were once ranked as a lower priority to a higher priority. A review is required for each new risk hazard, i.e. the starting of a new project; changes to the workplace, work procedure, process or flow; changing tools, equipment, and machinery; new employees; moving to a new building or work area; or if the occupational health and safety representative requests a review.

However, risks should be reviewed habitually or based on the seriousness of the safety risks to ensure that the risks of workers being harmed have not changed.

6.4 A Case Example: Safety Risk Assessment and Management for Building Construction Projects (Sansakorn and An, 2015)

A case example of falls from height in a building construction project is presented to demonstrate the proposed safety risk assessment model. Falls from height are considered as major injuries. It is crucial to undertake risk assessment for most projects, and proper risk management is required (Limsupreeyarat et al., 2010). In many cases, a worker falls from height due to improper scaffold construction, inadequacy of the edge protection, unprotected openings in buildings, lack of edge protection for working on roofs, dangerous demolition work or inappropriate use of ladders and hoists (OSHA, 1998; Hamid et al., 2008; OSHA, 2011). However, the FRT, based on the principle of fuzzy sets and fuzzy logic, offers advantages, which can be employed to reduce the uncertainty and vague information associated with building construction projects and activities. The application of the proposed methodology consists of six stages as stated in section 6.3, which are described in Section 6.4.1.

6.4.1 Safety Hazard Identification and Analysis

A safety risk management group is established to undertake the review of safety risks on a building construction site. The safety risk management group consisting of five experts is required to have appropriate knowledge and qualifications. A contribution factor is allocated to each expert, as shown in Table 6-11.

Table 6-11: Experts' contribution factor

Experts	Background	Contribution factor
E_1	Safety Manager	0.25
E_2	Project Manager	0.23
E_3	Senior Safety Officer	0.20
E_4	Safety Officer with 15 years' experience	0.17
E_5	Site Engineer with 15 years' experience	0.15

6.4.2 Safety Risk Criteria

(1) Determination of PO, SC, PC, RM, and membership functions of PO, SC, PC and RM

Three fundamental risk parameters, PO, SC and PC, are used to assess the risk magnitude of a construction project. PO is classified into five levels: "Very unlikely", "Unlikely", "Fairly unlikely", "Likely", and "Very likely". PC is classified into six levels: "Highly unlikely", "Unlikely", "Reasonably unlikely", "Likely", "Reasonably likely", and "Highly likely". SC is is classified into five levels: "Negligible", "Minor", "Moderate", "Major", and "Catastrophic". RM is classified into five levels: "Low", "Acceptable", "Average", "High", and "Unacceptable", as shown in Tables 6-6-6-9 respectively. PO, PC, SC and RM are defined by a trapezoidal MF_f, as shown in Figures. 6-3-6-6 respectively.

(2) *Fuzzy aggregation*

Experts in the Safety risk management team can provide a numerical value, a linguistic term, a range of numbers, a triangular fuzzy number and a trapezoidal fuzzy number to describe a specific identified hazard. In this case example, Expert E_1 uses a range of numbers, E_2 uses a numerical value, and E_4 uses a triangular fuzzy number, while E_3 and E_5 use linguistic terms, as shown in Table 6-12, to describe the hazard group falls from height.

The aggregated scores of PO scores can be calculated

$$\text{Probability of occurrence } \mu(x)$$
$$= \big((2,2,4,4) \times 0.25 + (3,3,3,3) \times 0.23 + (3,4,4,5) \times 0.20$$
$$+ (2,3,3,4) \times 0.17 + (3,3.5,4,4.5) \times 0.15\big)$$
$$= (2.58,\ 3.03,\ 3.60,\ 4.05)$$

$$\text{Probability of occurrence } \mu(x) = (2.58,\ 3.03,\ 3.60,\ 4.05)$$

Similarly, the aggregated scores of SC and PC can be obtained, as shown in Table 6-12.

$$\text{Severity of occurrence } \mu(x) = (3.81, 4.26, 4.58, 4.93)$$

$$\text{Probability of consequence } \mu(x) = (3.43, 3.87, 4.27, 4.72)$$

Table 6-12: Evaluation and STFN of PO, SC, and PC

Experts	Evaluation					
	Probability of occurrence		Severity of consequence		Probability of consequence	
	Score	Converted STFN	Score	Converted STFN	Score	Converted STFN
E_1	(2,4)	(2,2,4,4)	(4,5)	(4,4,5,5)	(3,4)	(3,3,4,4)
E_2	3	(3,3,3,3)	5	(5,5,5,5)	4	(4,4,4,4)
E_3	About 4	(3,4,4,5)	About 4.5	(3.5,4.5,4.5,5)	About 4.5	(3.5,4.5,4.5,5.5)
E_4	(2,3,4)	(2,3,3,4)	(3,4,5)	(3,4,4,5)	(4,5,6)	(4,5,5,6)
E_5	Likely	(3,3.5,4,4.5)	Major	(3,3.5,4,4.5)	Likely	(2.5,3,4,4.5)
Aggregated STFN	(2.58, 3.03, 3.60, 4.05)		(3.81, 4.26, 4.58, 4.93)		(3.43, 3.87, 4.27, 4.72)	

(3) Fuzzy inference

This step is to convert the aggregation of PO, SC, and PC into matching fuzzy sets for fuzzy inference. For example, the aggregated STFN of PO = (2.58, 3.03, 3.60, 4.05), as shown in Figure 6-9 (the thick segments), and then the matching fuzzy set PO is obtained by intersections between the STFN and fuzzy sets of PO:

$$PO = \{(Fairly\ unlikely,\ 0.975),\ (Likely,\ 1.000),\ (Very\ likely,\ 0.050)\}$$

Similarly, SC and PC can be obtained, the matching fuzzy sets of SC and PC as shown in Figures 6-9 - 6-11, are

$$SC = \{(Major,\ 0.728),\ (Catastrophic,\ 1.000)\}$$

$$PC = \{(Likely,\ 1.000),\ (Reasonable\ likely,\ 0.760)\}$$

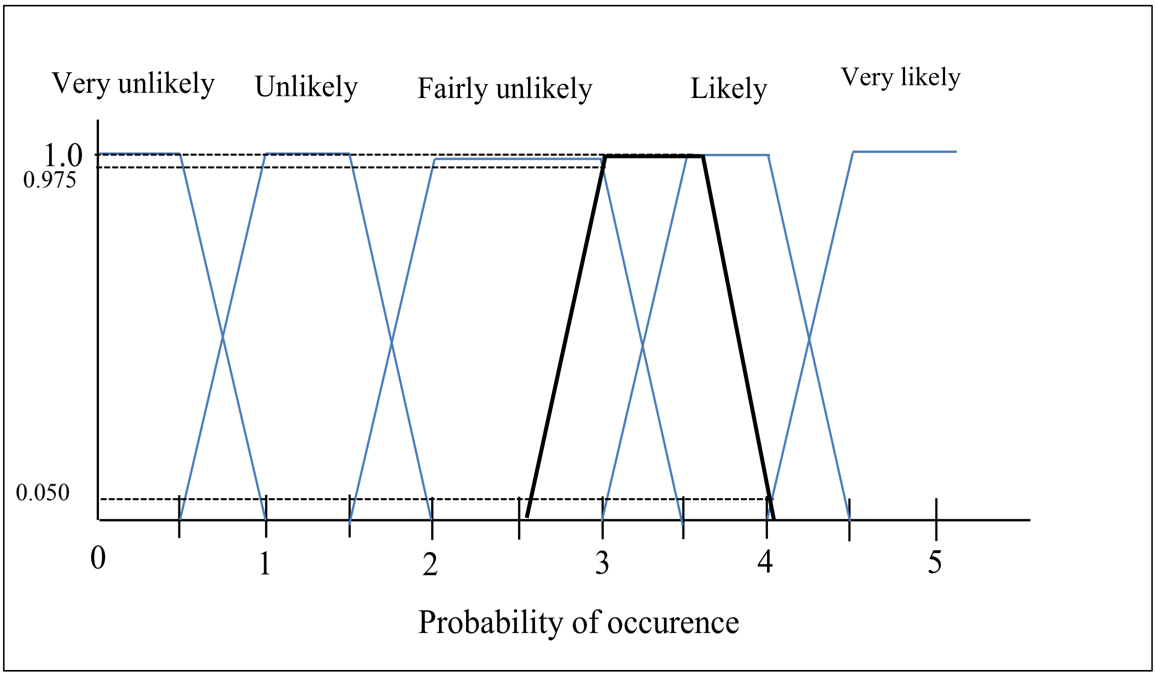


Figure 6-9: The matching fuzzy set PO

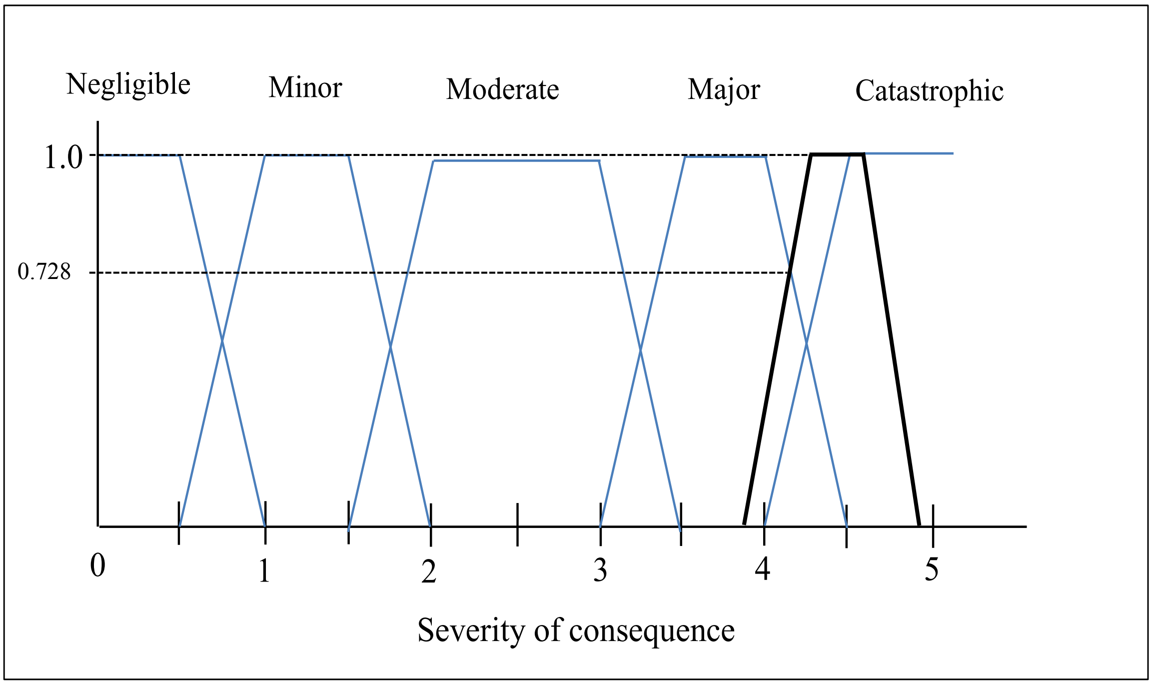


Figure 6-10: The matching fuzzy set SC

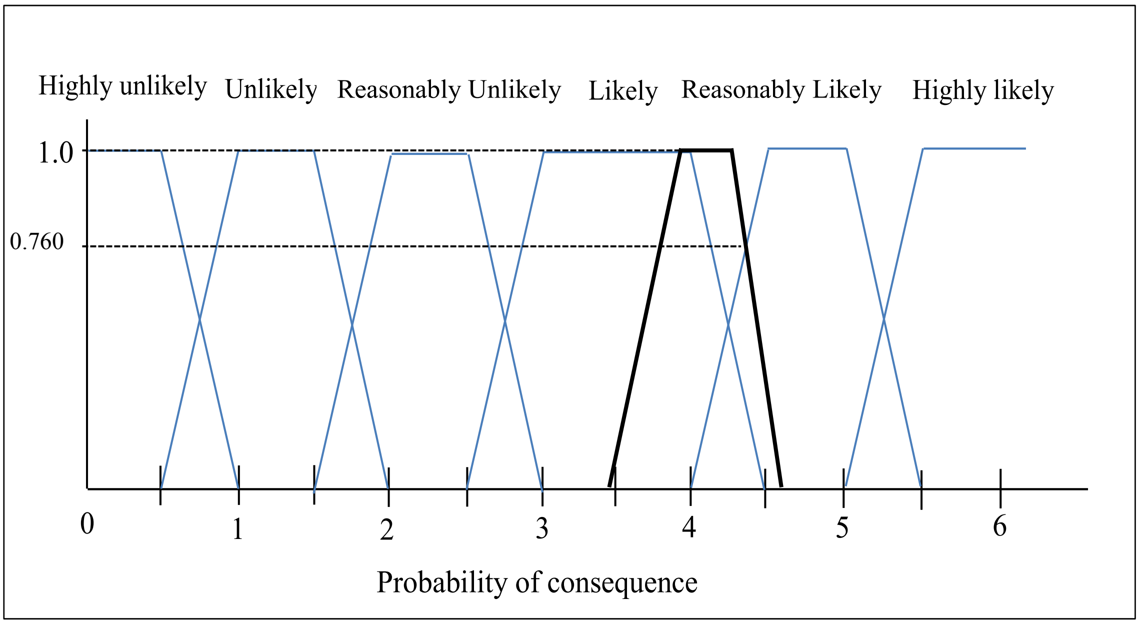


Figure 6-11: The matching fuzzy set PC

The safety risk management team produced 150 rules in the fuzzy rule base that are used in this study, as shown in Figure 6-12a and Figure 6-12b. The rules are interpreted thus: If PO is *Very unlikely* and SC is *Negligible* and PC is *Highly unlikely,* then RM is *Low*; and if PO is *Very likely* and SC is *Catastrophic* and PC is *Highly likely*, then RM is *Unacceptable.*

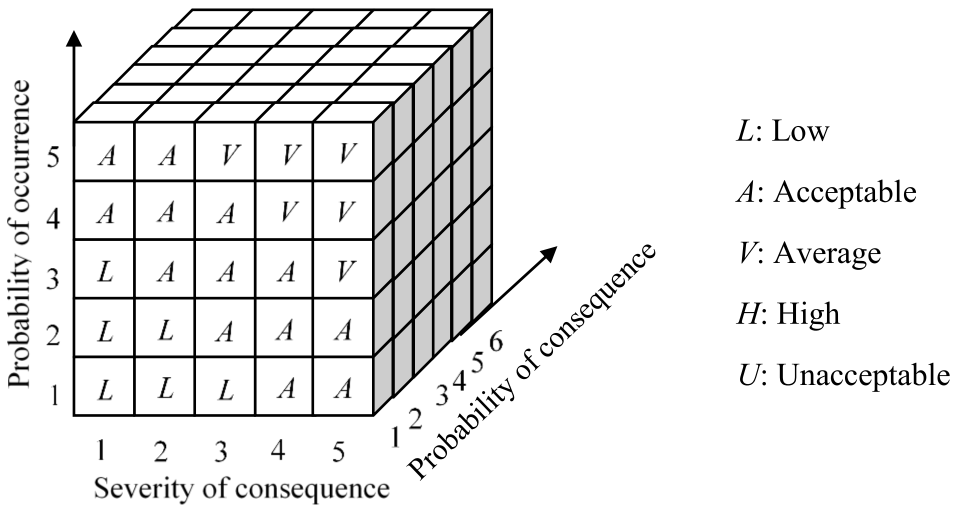


Figure 6-12a: The multidimensional fuzzy rule base matrices

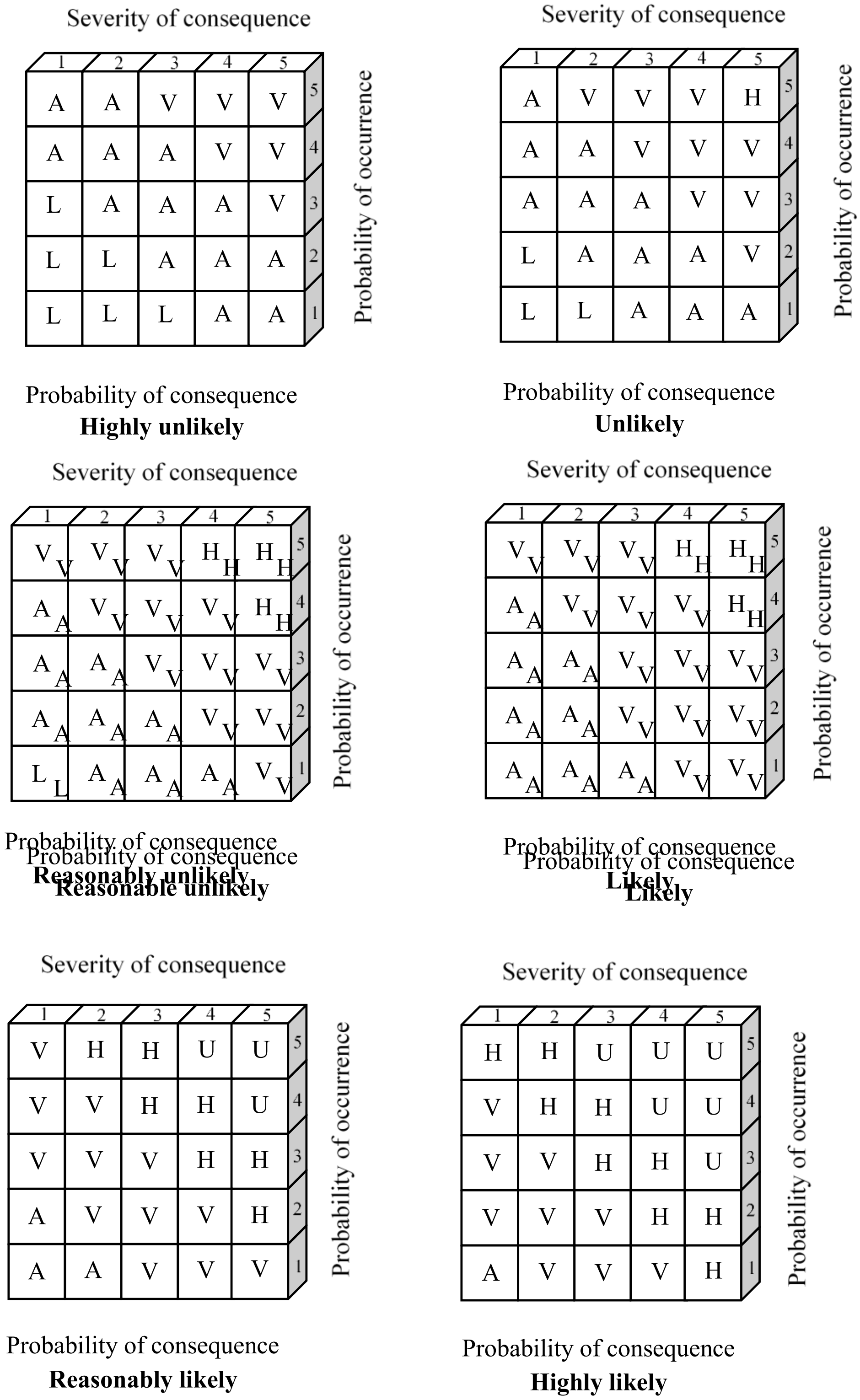


Figure 6-12b: Fuzzy rule base matrices (adapted from An et al, 2011)

For a three-by-one system, the fuzzy rule base develops the shape of a $PO \times SC \times PC$ cube, as shown in Figure 6-12.

The min-max implication is then employed in this case study example to calculate fuzzy preference. The fuzzy inference can be broken down into four steps, as described below (Zeng, 2005).

Determining which rule is on the rule base. From the mapping of inputs of $PO \times SC \times PC$, the following 12 rules are fired, contributing to the actual evaluation process. These 12 rules are:

Rule #106: If PO is FU_{PO} and SC is MA_{SC} and PC is LI_{PC}, then RM is A

Rule #107: If PO is FU_{PO} and SC is MA_{SC} and PC is RL_{PC}, then RM is H

Rule #112: If PO is LI_{PO} and SC is MA_{SC} and PC is LI_{PC}, then RM is H

Rule #113: If PO is LI_{PO} and SC is MA_{SC} and PC is RL_{PC}, then RM is H

Rule #118: If PO is VL_{PO} and SC is MA_{SC} and PC is LI_{PC}, then RM is H

Rule #119: If PO is VL_{PO} and SC is MA_{SC} and PC is RL_{PC}, then RM is U

Rule #136: If PO is FU_{PO} and SC is CA_{SC} and PC is LI_{PC}, then RM is H

Rule #137: If PO is FU_{PO} and SC is CA_{SC} and PC is RL_{PC}, then RM is H

Rule #142: If PO is LI_{PO} and SC is CA_{SC} and PC is LI_{PC}, then RM is H

Rule #143: If PO is LI_{PO} and SC is CA_{SC} and PC is RL_{PC}, then RM is U

Rule #148: If PO is VL_{PO} and SC is CA_{SC} and PC is LI_{PC}, then RM is U

Rule #149: If PO is VL_{PO} and SC is CA_{SC} and PC is RL_{PC}, then RM is U

(1) Taking the minimum operator to calculate the strength of the fired rules, the process is shown as follows:

$$Rule\ \#\ 106\text{: } \alpha_{106} = \mu\, FU(PO) \cap \mu MA(SC) \cap \mu LI(PC) = min(0.975, 0.728, 1.000) = 0.728$$

$$Rule\ \#107\text{: } \alpha_{107} = \mu\, FU(PO) \cap \mu MA(SC) \cap \mu RL(PC) = min(0.975, 0.728, 0.760) = 0.728$$

$$Rule\ \#112\text{: } \alpha_{112} = \mu\, LI(PO) \cap \mu MA(SC) \cap \mu LI(PC) = min(1.000, 0.728, 1.000) = 0.728$$

$$Rule\ \#113\text{: } \alpha_{113} = \mu\, LI(PO) \cap \mu MA\ (SC) \cap \mu RL(PC) = min(1.000, 0.728, 0.760) = 0.728$$

$Rule$ #118: $\alpha_{118} = \mu VL(PO) \cap \mu MA(SC) \cap \mu LI(PC) = min(0.050,\ 0.728,\ 1.000) = 0.050$

$Rule$ #119: $\alpha_{119} = \mu VL(PO) \cap \mu MA(SC) \cap \mu RL(PC) = min(0.050,\ 0.728,\ 0.760) = 0.050$

$Rule$ #136: $\alpha_{136} = \mu FU(PO) \cap \mu CA(SC) \cap \mu LI(PC) = min(0.975,\ 1.000, 1.000) = 0.975$

$Rule$ #137: $\alpha_{137} = \mu FU(PO) \cap \mu CA(SC) \cap \mu RL(PC) = min(0.975, 1.000, 0.760) = 0.760$

$Rule$ #142: $\alpha_{142} = \mu LI(PO) \cap \mu CA(SC) \cap \mu LI(PC) = min(1.000, 1.000, 1.000) = 1.000$

$Rule$ #143: $\alpha_{143} = \mu LI(PO) \cap \mu CA(SC) \cap \mu RL(PC) = min(1.000,\ 1.000,\ 0.760) = 0.760$

$Rule$ # 148: $\alpha_{148} = \mu VL(PO) \cap \mu CA(SC) \cap \mu LI(PC) = min(0.050,\ 1.000,\ 1.000) = 0.050$

$Rule$ #149: $\alpha_{149} = \mu VL(PO) \cap \mu CA(SC) \cap \mu RL(PC) = min(0.050,\ 1.000,\ 0.760) = 0.050$

where FU_{PO}, LI_{PO}, and VL_{PO} are the qualitative descriptors, "*Fairly unlikely*", "*Likely*", and "*Very likely*" of PO, respectively and MA_{SC} and CA_{SC} are the qualitative descriptors, "*Major*" and "*Catastrophic*" of SC and LI_{PC}, RL_{PC}, are the qualitative descriptors, "*Likely*" and "*Reasonably likely*" of PC respectively.

(2) Determine the control fired rules in outputs:

$Rule$ #106 : $\alpha_{106} \cap \mu V(RM) = min\ (0.728,\ \mu V(RM)\ )$

$Rule$ #107 : $\alpha_{107} \cap \mu H(RM) = min\ (0.728,\ \mu H(RM)\ )$

$Rule$ #112 : $\alpha_{112} \cap \mu H(RM) = min\ (0.728,\ \mu H(RM)\ )$

$Rule$ #113 : $\alpha_{113} \cap \mu H(RM) = min\ (0.728,\ \mu H(RM)\ )$

$Rule$ #118 : $\alpha_{118} \cap \mu H(RM) = min\ (0.050,\ \mu H(RM)\ )$

$Rule$ #119 : $\alpha_{119} \cap \mu U(RM) = min\ (0.050,\ \mu U(RM)\ )$

$Rule$ #136 : $\alpha_{136} \cap \mu H(RM) = min\ (0.975,\ \mu H(RM)\ )$

$Rule$ #137 : $\alpha_{137} \cap \mu H(RM) = min\ (0.760,\ \mu H(RM)\ )$

$Rule$ #142 : $\alpha_{142} \cap \mu H(RM) = min\ (1.000,\ \mu H(RM)\ )$

$Rule$ #143 : $\alpha_{143} \cap \mu U(RM) = min\ (0.760,\ \mu U(RM)\ )$

$Rule$ #148 : $\alpha_{148} \cap \mu U(RM) = min\ (0.050,\ \mu U(RM)\ )$

$Rule$ #149 : $\alpha_{149} \cap \mu U(RM) = min\ (0.050,\ \mu U(RM)\ )$

It should be noted that the following rules

Rule #107, *Rule* #112, *Rule* #113, *Rule* #118, *Rule* #136, and *Rule* #137 are included in *Rule* #142, and then *Rule* #119, *Rule* #148 and *Rule* #149 are included in *Rule* #143.

Taking the maximum operator to calculate

$$\mu Q^{i}{}_{RM'}(x) = \max\{\min(0.728,\ \mu V(RM)),\ \min(1.000,\ \mu H(RM)), \min(0.760,\ \mu U(RM))\}$$

(4) Defuzzification

This step is to convert the fuzzy output RM into a matching numerical value of RM. By using the centre average calculation method, the crisp value is obtained RM= 4.013 is obtained, which gives the position of RM estimation in the axis of the risk magnitude, as shown in Figure 6-13

$$RM = \frac{3 \times 0.728 + 4 \times 1.00 + 5 \times 0.760}{0.728 + 1.000 + 0.760} = 4.013$$

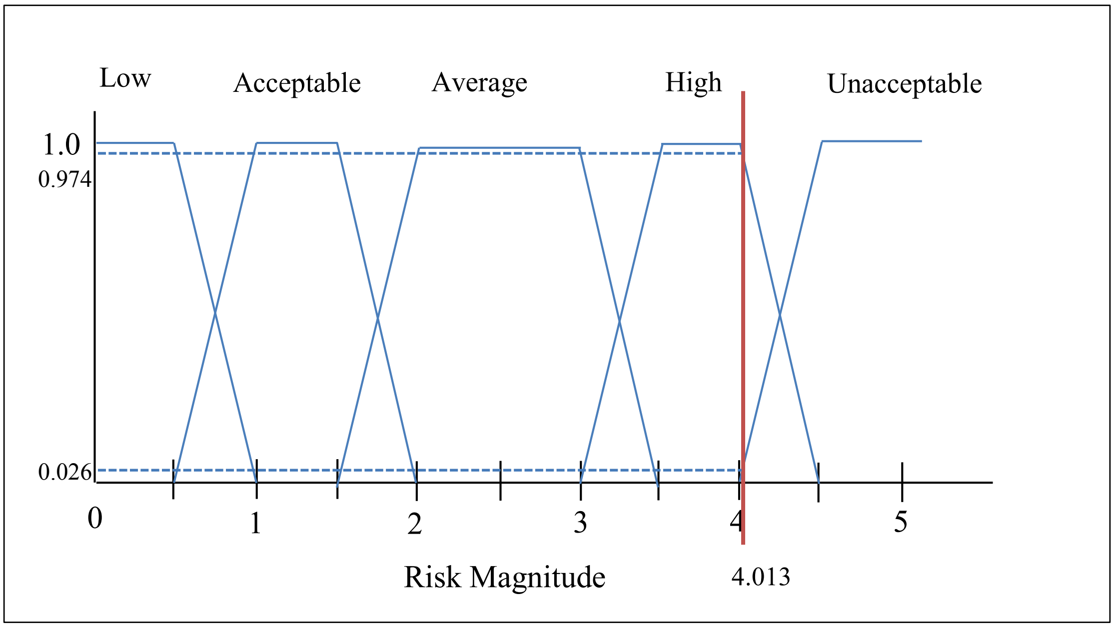


Figure 6-13: Defuzzification of RM

6.4.3 Safety Risk Estimation (Sansakorn and An, 2015)

The overall safety risk magnitude is 4.013 under the defined scale system of RM, i.e. the safety risk of falls from height is between *High* and *Unacceptable* with confidence of 97.4 per cent (μ = 0.974) for *High* and 2.6 per cent (μ = 0.026) for *Unacceptable*. This value requires risk reduction measures to be implemented to reduce the risk level of falls from height on building construction projects and provides useful information for safety managers, safety officers and safety analysts to carry out safety-based decision-making. The appropriate corrective and preventive actions in this building construction project management are provided.

6.4.4 Safety Risk Ranking

Once the particular safety risks of building projects, including falls from height (FH), falling objects (FO), manual handling (MH), equipment, machinery and tools (EQ), electricity (EL), slips and trips (ST), traffic hazards (TH), vehicle overturn (VO), fire and explosions (FE), exposure to hazardous substances (ES), radiation hazards (RH), collapse of site structure (CO), ergonomic/human factors (EH), confined spaces (CS), and noise and vibration (NV), have been identified based on previous accident reports and the safety risk management team's judgement, an MFAHP is applied in the following section.

6.4.4.1 Calculation of the criteria weight by using a modified fuzzy analytical hierarchy process (MFAHP)

At this stage, the risk management team were asked to make pairwise comparisons of 15 safety risks by using fuzzy linguistic variables. Nine linguistic variables were used to capture the subjective judgements of the relative importance of the risks (An et al., 2016), as shown in Table 5-1.

According to the basic principles, the experts were asked to make pairwise judgements of all risks. It should be noted that *n* (*n*-1)/2, as mentioned earlier, and in this case, 15 × (15-1)/2 = 105 comparisons. According to Equations (5-2), and (5-3), however, using the MFAHP method using only *n*-1, (15-1) = 14 comparisons can be obtained (An et al., 2016). Then, aggregated pairwise comparison values were obtained by Equation (6-3). For example, the aggregated STFN pairwise comparison of FH vs. FO ($x_{1,2}$) is as follows:

$$\text{FH vs. FO}_a = \left\{\frac{1\times0.25+2\times0.23+2\times0.20+1\times0.17+1\times0.15}{0.25+0.23+0.20+0.17+0.15}\right\} = 1.43$$

$$\text{FH vs. FO}_b = \left\{\frac{2\times0.25+3\times0.23+3\times0.20+2\times0.17+2\times0.15}{0.25+0.23+0.20+0.17+0.15}\right\} = 2.43$$

$$\text{FH vs. FO}_c = \left\{\frac{2\times0.25+3\times0.23+3\times0.20+2\times0.17+2\times0.15}{0.25+0.23+0.20+0.17+0.15}\right\} = 2.43$$

$$\text{FH vs. FO}_d = \left\{\frac{3\times0.25+4\times0.23+4\times0.20+3\times0.17+3\times0.15}{0.25+0.23+0.20+0.17+0.15}\right\} = 3.43$$

FH vs. FO $\{a, b, c, d\} = \{1.43, 2.43, 2.43, 3.43\}$

Finally, the aggregated STFN of 14 pairwise comparisons were obtained, as shown in Table 6-13, which will be used to establish the fuzzy preference relation decision matrix.

Table 6-13: Pairwise comparison of the safety risks

Comparison	Aggregated STFN
FH vs FO ($x_{1,2}$)	(1.43,2.43,2.43,3.43)
FO vs MH ($x_{2,3}$)	(1.23,1.78,1.78,2.78)
MH vs EQ ($x_{3,4}$)	(3.66,4.66,4.66,5.66)
EQ vs EL ($x_{4,5}$)	(2.25,3.25,3.25,4.25)
EL vs ST ($x_{5,6}$)	(5.00,6.00,6.00,7.00)
ST vs TH ($x_{6,7}$)	(6.37,7.37,7.37,8.37)
TH vs VO ($x_{7,8}$)	(6.52,7.52,7.52,8.52)
VO vs FE ($x_{8,9}$)	(2.95,3.95,3.95,4.95)
EF vs ES ($x_{9,10}$)	(7.06,8.06,8.06,8.83)
ES vs RH ($x_{10,11}$)	(3.63,4.63,4.63,5.63)
RH vs CO ($x_{11,12}$)	(2.80,3.80,3.80,4.80)
CO vs EH ($x_{12,13}$)	(4.37,5.37,5.37,6.37)
EH vs CS ($x_{13,14}$)	(3.08,4.08,4.08,5.08)
CS vs NV ($x_{14,15}$)	(6.35,7.35,7.35,8.35)

Then, the completed transformation fuzzy number relation decision matrix of all the safety risks can be obtained according to Equation (5-1) as follows:

For example, the calculation of trapezoidal fuzzy number pairwise comparison of
FO vs. FH ($x_{2,1}$)

$X_{1,2} = \{a_{i,j}, b_{i,j}, c_{i,j}, d_{i,j}\}, X_{2,1} = \{1/d_{i,j}, 1/c_{i,j}, 1/b_{i,j}, 1/a_{i,j}\}$

$FO_{1,2} = \{1.43, 2.43, 2.43, 3.43\}$,

$FO_{2,1} = \{1/ (3.43), 1/ (2.43), 1/ (2.43), 1/ (1.43)\}$

$FO_{2,1} = \{0.29, 0.41, 0.41, 0.70\}$

and FO $_{2,15}$ can be obtained by Equation (5-7) as follows:

$FO_{2,\,15\,a} = a_{2,3} \times a_{3,4} \times a_{4,5} \times a_{5,6} \times a_{6,7} \times a_{7,8} \times a_{8,9} \times a_{9,10} \times a_{10,11} \times a_{11,12} \times a_{12,13} \times a_{13,14} \times a_{14,15}$

$FO_{2,\,15\,a}$ = 1.23× 3.66× 2.55× 5.00× 6.37 × 6.52 × 2.95 × 7.06 ×3.63 ×2.80 × 4.37 × 3.08 × 6.35 = 3.8E+07

$FO_{2,\,15\,b} = b_{2,3} \times b_{3,4} \times b_{4,5} \times b_{5,6} \times b_{6,7} \times b_{7,8} \times b_{8,9} \times b_{9,10} \times b_{10,11} \times b_{11,12} \times b_{12,13} \times b_{13,14} \times b_{14,15}$

$FO_{2,\,15\,b}$ = 1.78× 4.66× 3.55×6.00× 7.37 × 7.52 × 3.95×8.06 × 4.63 ×3.80 ×5.37 × 4.08 × 7.35 = 8.1E+08

$FO_{2,\,15\,c} = c_{2,3} \times c_{3,4} \times c_{4,5} \times c_{5,6} \times c_{6,7} \times c_{7,8} \times c_{8,9} \times c_{9,10} \times c_{10,11} \times c_{11,12} \times c_{12,13} \times c_{13,14} \times c_{14,15}$

$FO_{2,\,15\,c}$ = 1.78× 4.66× 3.55× 6.00× 7.37 × 7.52 × 3.95 × 8.06 × 4.63 × 3.80 × 5.37 × 4.08 × 7.35 = 8.1E+08

$FO_{2,\,15\,d} = d_{2,3} \times d_{3,4} \times d_{4,5} \times d_{5,6} \times d_{6,7} \times d_{7,8} \times d_{8,9} \times d_{9,10} \times d_{10,11} \times d_{11,12} \times d_{12,13} \times d_{13,14} \times d_{14,15}$

$FO_{2,\,15\,d}$ = 2.78× 5.66× 4.55× 7.00× 8.37 × 8.52 × 4.95 × 8.83 × 5.63 × 4.80 × 6.37 × 5.08 × 8.35 = 1.1E+10

$FO_{2,\,15}$ {*a, b, c, d*} = {3.8E+07, 8.1E+08, 8.1E+08, 1.1E+10}

Using Equations (5-1), and (5-7), the completed trapezoidal fuzzy number preference relation decision matrix is shown in Table 6-14.

It should be noted that $FH_{1,3}$ and $FH_{1,15}$ are not in the interval [1/9-9]. The completed trapezoidal fuzzy number preference relation decision matrix is needed to transfer the MFAHP preference relation decision matrix in the interval. In this case, by using Equation (5-8), the maximum of $D = max\ (x_{ij}) = x_{1,\,15}$ = 3.6E+10 and the following transformation functions are applied as (An *et al.*, 2016).

Table 6-14: Completed trapezoidal fuzzy number preference relation decision matrix

	FH	FO	MH	EQ	EL	ST	TH	VO	EF	ES	RH	CO	EH	CS	NV
FH	1.00, 1.00, 1.00, 1.00	1.43, 2.43, 2.43, 3.43	1.76, 4.33, 4.33, 9.54	6.44, 20.16, 20.16, 53.97	14.48, 65.51, 65.51, 229.37	72.42, 393.05, 393.05, 1.6E+03	461.33, 2.9E+03, 2.9E+03, 1.3E+04	3.0E+03, 2.2E+04, 2.2E+04, 1.1E+05	8.9E+03, 8.6E+04, 8.6E+04, 5.7E+05	6.3E+04, 6.9E+05, 6.9E+05, 5.0E+06	2.3E+05, 3.2E+06, 3.2E+06, 2.8E+07	6.4E+05, 1.2E+07, 1.2E+07, 1.4E+08	2.8E+06, 6.6E+07, 6.6E+07, 8.6E+08	8.6E+06, 2.7E+08, 2.7E+08, 4.4E+09	5.4E+07, 1.9E+09, 1.9E+09, 3.6E+10
FO	0.29, 0.41, 0.41, 0.70	1.00, 1.00, 1.00, 1.00	1.23, 1.78, 1.78, 2.78	4.50, 8.29, 8.29, 15.73	10.13, 26.96, 26.96, 66.87	50.65, 161.75, 161.75, 468.11	322.61, 1.2E+03, 1.2E+03, 3.9E+03	2.1E+03, 9.0E+03, 9.0E+03, 3.3E+04	6.2E+03, 3.5E+04, 3.5E+04, 1.7E+05	4.4E+04, 2.9E+05, 2.9E+05, 1.5E+06	1.6E+05, 1.3E+06, 1.3E+06, 8.2E+06	4.5E+05, 5.0E+06, 5.0E+06, 3.9E+07	1.9E+06, 2.7E+07, 2.7E+07, 2.5E+08	5.9E+06, 1.1E+08, 1.1E+08, 1.3E+09	3.8E+07, 8.1E+08, 8.1E+08, 1.1E+10
MH	0.10, 0.23, 0.23, 0.57	0.36, 0.56, 0.56, 0.81	1.00, 1.00, 1.00, 1.00	3.66, 4.66, 4.66, 5.66	8.24, 15.15, 15.15, 24.06	41.18, 90.87, 90.87, 168.39	262.28, 6.7E+02, 6.7E+02, 1.4E+03	1.7E+03, 5.0E+03, 5.0E+03, 1.2E+04	5.0E+03, 2.0E+04, 2.0E+04, 5.9E+04	3.6E+04, 1.6E+05, 1.6E+05, 5.2E+05	1.3E+05, 7.4E+05, 7.4E+05, 2.9E+06	3.6E+05, 2.8E+06, 2.8E+06, 1.4E+07	1.6E+06, 1.5E+07, 1.5E+07, 9.0E+07	1.9E+06, 2.7E+07, 2.7E+07, 2.5E+08	3.1E+07, 4.5E+08, 4.5E+08, 3.8E+09
EQ	0.02, 0.05, 0.05, 0.16	0.06, 0.12, 0.12, 0.22	0.18, 0.21, 0.21, 0.27	1.00, 1.00, 1.00, 1.00	2.25, 3.25, 3.25, 4.25	11.25, 19.50, 19.50, 29.75	71.66, 143.72, 143.72, 249.01	4.7E+02, 1.1E+03, 1.1E+03, 2.1E+03	1.4E+03, 4.3E+03, 4.3E+03, 1.1E+04	9.7E+03, 3.4E+04, 3.4E+04, 9.3E+04	3.5E+04, 1.6E+05, 1.6E+05, 5.2E+05	9.9E+04, 6.1E+05, 6.1E+05, 2.5E+06	4.3E+05, 3.2E+06, 3.2E+06, 1.6E+07	1.3E+06, 1.3E+07, 1.3E+07, 8.1E+07	8.4E+06, 9.7E+07, 9.7E+07, 6.8E+08
EL	4.4E-03, 0.02, 0.02, 0.07	0.01, 0.04, 0.04, 0.10	0.04, 0.07, 0.07, 0.12	0.24, 0.31, 0.31, 0.44	1.00, 1.00, 1.00, 1.00	5.00, 6.00, 6.00, 7.00	31.85, 44.22, 44.22, 58.59	207.66, 332.53, 332.53, 499.19	6.1E+02, 1.3E+03, 1.3E+03, 2.5E+03	4.3E+03, 1.1E+04, 1.1E+04, 2.2E+04	1.5E+04, 4.9E+04, 4.9E+04, 1.2E+05	4.4E+04, 1.9E+05, 1.9E+05, 5.9E+05	1.9E+05, 1.0E+06, 1.0E+06, 3.7E+06	5.9E+05, 4.1E+06, 4.1E+06, 1.9E+07	1.3E+06, 1.3E+07, 1.3E+07, 8.1E+07
ST	6.2E-04, 2.5E-03, 2.5E-03, 1.4E-02	2.1E-03, 0.01, 0.01, 0.02	0.01, 0.01, 0.01, 0.02	0.03, 0.05, 0.05, 0.09	0.14, 0.17, 0.17, 0.20	1.00, 1.00, 1.00, 1.00	6.37, 7.37, 7.37, 8.37	41.53, 55.42, 55.42, 71.31	122.52, 218.92, 218.92, 353.00	865.00, 1.8E+03, 1.8E+03, 3.1E+03	3.1E+03, 8.2E+03, 8.2E+03, 1.7E+04	8.8E+03, 3.0E+04, 3.1E+04, 8.4E+04	3.8E+04, 1.7E+05, 1.7E+05, 5.4E+05	1.2E+05, 6.8E+05, 6.8E+05, 2.7E+06	7.5E+05, 5.0E+06, 5.0E+06, 2.3E+07
TH	7.4E-05, 3.5E-04, 3.5E-04, 2.2E-03	2.6E-04, 8.4E-04, 8.4E-04, 3.1E-03	7.1E-04, 1.5E-03, 1.5E-03, 3.8E-03	4.0E-03, 7.0E-03, 7.0E-03, 1.4E-02	1.7E-02, 2.3E-02, 2.3E-02, 3.1E-02	0.12, 0.14, 0.14, 0.16	1.00, 1.00, 1.00, 1.00	6.52, 7.52, 7.52, 8.52	19.23, 29.70, 29.70, 42.17	135.79, 239.41, 239.41, 372.40	4.9E+02, 1.1E+03, 1.1E+03, 2.1E+03	1.3E+03, 4.2E+03, 4.2E+03, 1.0E+04	6.0E+03, 2.3E+04, 2.3E+04, 6.4E+04	1.9E+04, 9.2E+04, 9.2E+04, 3.3E+05	1.2E+05, 6.8E+05, 6.8E+05, 2.7E+06
VO	8.7E-06, 4.6E-05, 4.6E-05, 3.3E-04	3.0E-05, 1.1E-04, 1.1E-04, 4.8E-04	8.3E-05, 2.0E-04, 2.0E-04, 5.8E-04	4.7E-04, 9.3E-04, 9.3E-04, 2.1E-03	2.0E-03, 3.0E-03, 3.0E-03, 4.8E-03	1.4E-02, 1.8E-02, 1.8E-02, 2.4E-02	0.12, 0.13, 0.13, 0.15	1.00, 1.00, 1.00, 1.00	2.95, 3.95, 3.95, 4.95	20.83, 31.84, 31.84, 43.71	75.60, 147.41, 147.41, 246.08	211.69, 560.14, 560.14, 1181.18	9.2E+02, 3.0E+03, 3.0E+03, 7.5E+03	2.8E+03, 1.2E+04, 1.2E+04, 3.8E+04	1.8E+04, 9.0E+04, 9.0E+04, 3.2E+05
EF	1.8E-06, 1.2E-05, 1.2E-05, 1.1E-04	6.1E-06, 2.8E-05, 2.8E-05, 1.6E-04	1.7E-05, 5.0E-05, 5.0E-05, 2.0E-04	9.5E-05, 2.3E-04, 2.3E-04, 7.3E-04	4.0E-04, 7.6E-04, 7.6E-04, 1.6E-03	2.8E-03, 4.6E-03, 4.6E-03, 8.2E-03	0.02, 0.03, 0.03, 0.05	0.20, 0.25, 0.25, 0.34	1.00, 1.00, 1.00, 1.00	7.06, 8.06, 8.06, 8.83	25.63, 37.32, 37.32, 49.71	71.76, 141.81, 141.81, 238.62	3.1E+02, 7.6E+02, 7.6E+02, 1.5E+03	9.6E+02, 3.1E+03, 3.1E+03, 7.7E+03	6.1E+03, 2.2E+04, 2.2E+04, 6.4E+04

Table 6-14: Completed trapezoidal fuzzy number preference relation decision matrix (cont.)

	FH	FO	MH	EQ	EL	ST	TH	VO	EF	ES	RH	CO	EH	CS	NV
ES	2.0E-07, 1.4E-06, 1.4E-06, 1.6E-05	6.9E-07, 3.5E-06, 3.5E-06, 2.3E-05	1.9E-06, 6.2E-06, 6.2E-06, 2.8E-05	1.1E-05, 2.9E-05, 2.9E-05, 1.0E-04	4.6E-05, 9.4E-05, 9.4E-05, 2.3E-04	3.2E-04, 5.7E-04, 5.7E-04, 1.2E-03	2.7E-03, 4.2E-03, 4.2E-03, 7.4E-03	0.02, 0.03, 0.03, 0.05	0.11, 0.12, 0.12, 0.14	1.00, 1.00, 1.00, 1.00	3.63, 4.63, 4.63, 5.63	10.16, 17.59, 17.59, 27.02	44.42, 94.48, 94.48, 172.14	136.80, 385.48, 385.48, 874.49	8.7E+02, 2.8E+03, 2.8E+03, 7.3E+03
RH	3.5E-08, 3.1E-07, 3.1E-07, 4.4E-06	1.2E-07, 7.6E-07, 7.6E-07, 6.3E-06	3.4E-07, 1.3E-06, 1.3E-06, 7.7E-06	1.9E-06, 6.3E-06, 6.3E-06, 2.8E-05	8.1E-06, 2.0E-05, 2.0E-05, 6.4E-05	5.7E-05, 1.2E-04, 1.2E-04, 3.2E-04	4.8E-04, 9.0E-04, 9.0E-04, 2.0E-03	4.1E-03, 6.8E-03, 6.8E-03, 1.3E-02	0.02, 0.03, 0.03, 0.04	0.18, 0.22, 0.22, 0.28	1.00, 1.00, 1.00, 1.00	2.80, 3.80, 3.80, 4.80	12.24, 20.41, 20.41, 30.58	37.69, 83.26, 83.26, 155.33	239.31, 611.94, 611.94, 1296.97
CO	7.4E-09, 8.2E-08, 8.2E-08, 1.6E-06	2.5E-08, 2.0E-07, 2.0E-07, 2.2E-06	7.1E-08, 3.5E-07, 3.5E-07, 2.8E-06	4.0E-07, 1.7E-06, 1.7E-06, 1.0E-05	1.7E-06, 5.4E-06, 5.4E-06, 2.3E-05	1.2E-05, 3.2E-05, 3.2E-05, 1.1E-04	9.9E-05, 2.4E-04, 2.4E-04, 7.2E-04	8.5E-04, 1.8E-03, 1.8E-03, 4.7E-03	4.2E-03, 7.1E-03, 7.1E-03, 1.4E-02	0.04, 0.06, 0.06, 0.10	0.21, 0.26, 0.26, 0.36	1.00, 1.00, 1.00, 1.00	4.37, 5.37, 5.37, 6.37	13.46, 21.91, 21.91, 32.36	85.47, 161.04, 161.04, 270.20
EH	1.2E-09, 1.5E-08, 1.5E-08, 3.6E-07	4.0E-09, 3.7E-08, 3.7E-08, 5.1E-07	1.1E-08, 6.6E-08, 6.6E-08, 6.3E-07	6.3E-08, 3.1E-07, 3.1E-07, 2.3E-06	2.7E-07, 1.0E-06, 1.0E-06, 5.2E-06	1.9E-06, 6.0E-06, 6.0E-06, 2.6E-05	1.6E-05, 4.4E-05, 4.4E-05, 1.7E-04	1.3E-04, 3.3E-04, 3.3E-04, 1.1E-03	6.6E-04, 1.3E-03, 1.3E-03, 3.2E-03	5.8E-03, 1.1E-02, 1.1E-02, 2.3E-02	0.03, 0.05, 0.05, 0.08	0.16, 0.19, 0.19, 0.23	1.00, 1.00, 1.00, 1.00	3.08, 4.08, 4.08, 5.08	19.56, 29.99, 29.99, 42.42
CS	2.3E-10, 3.7E-09, 3.7E-09, 1.2E-07	7.8E-10, 9.1E-09, 9.1E-09, 1.7E-07	4.0E-09, 3.7E-08, 3.7E-08, 5.1E-07	1.2E-08, 7.5E-08, 7.5E-08, 7.5E-07	5.2E-08, 2.5E-07, 2.5E-07, 1.7E-06	3.7E-07, 1.5E-06, 1.5E-06, 8.5E-06	3.1E-06, 1.1E-05, 1.1E-05, 5.4E-05	2.6E-05, 8.1E-05, 8.1E-05, 3.5E-04	1.3E-04, 3.2E-04, 3.2E-04, 1.0E-03	1.1E-03, 2.6E-03, 2.6E-03, 7.3E-03	6.4E-03, 1.2E-02, 1.2E-02, 0.03	3.1E-02, 4.6E-02, 4.6E-02, 0.07	0.20, 0.25, 0.25, 0.32	1.00, 1.00, 1.00, 1.00	6.35, 7.35, 7.35, 8.35
NV	2.7E-11, 5.1E-10, 5.1E-10, 1.8E-08	9.4E-11, 1.2E-09, 1.2E-09, 2.6E-08	2.6E-10, 2.2E-09, 2.2E-09, 3.2E-08	1.5E-09, 1.0E-08, 1.0E-08, 1.2E-07	1.2E-08, 7.5E-08, 7.5E-08, 7.5E-07	4.4E-08, 2.0E-07, 2.0E-07, 1.3E-06	3.7E-07, 1.5E-06, 1.5E-06, 8.5E-06	3.1E-06, 1.1E-05, 1.1E-05, 5.5E-05	1.6E-05, 4.4E-05, 4.4E-05, 1.6E-04	1.4E-04, 3.5E-04, 3.5E-04, 7.3E-03	7.7E-04, 1.6E-03, 1.6E-03, 4.2E-03	3.7E-03, 6.2E-03, 0.01, 0.01	0.02, 0.03, 0.03, 0.05	8.6E+06, 2.7E+08, 2.7E+08, 4.4E+09	1.00, 1.00, 1.00, 1.00

$f(x_a) = x_a^{1/\log_9 3.6E+10}$, $f(x_b) = x_b^{1/\log_9 3.6E+10}$,

$f(x_c) = x_c^{1/\log_9 3.6E+10}$, $f(x_d) = x_d^{1/\log_9 3.6E+10}$

For example,

$$FH_a = 5.44E+07_a^{1/\log_9 3.6E+10} = 5.00$$

$$FH_b = 1.96E+09_b^{1/\log_9 3.6E+10} = 6.91$$

$$FH_c = 1.96E+09_c^{1/\log_9 3.6E+10} = 6.91$$

$$FH_d = 3.65E+09_d^{1/\log_9 3.6E+10} = 9.00$$

Finally, the MFAHP preference relation decision matrix is obtained, as shown in Table 6-15.

Using Equations (5-5), and (5-6), the geometric mean method and the weights of all safety hazards are obtained, and by using Equation (5-7), defuzzification is applied to convert them into crisp numbers.

For example, the total weight factors of falls from height (FH) are as follows:

$$X_{FH} = \{a_1, b_1, c_1, d_1\} = \begin{Bmatrix} \sqrt[15]{\prod_{j=1}^{15} a_{1j}}, \\ \sqrt[15]{\prod_{j=1}^{15} b_{1j}}, \\ \sqrt[15]{\prod_{j=1}^{15} c_{1j}}, \\ \sqrt[15]{\prod_{j=1}^{15} d_{1j}} \end{Bmatrix}$$

Table 6-15: MFAHP preference relation decision matrix

	FH	FO	MH	EQ	EL	ST	TH	VO	EF	ES	RH	CO	EH	CS	NV
FH	1.00, 1.00, 1.00, 1.00	1.03, 1.08, 1.08, 1.12	1.05, 1.14, 1.14, 1.23	1.18, 1.31, 1.31, 1.43	1.27, 1.46, 1.46, 1.63	1.47, 1.72, 1.72, 1.95	1.74, 2.05, 2.05, 2.36	2.06, 2.47, 2.47, 2.86	2.27, 2.79, 2.79, 3.31	2.71, 3.37, 3.37, 4.03	3.05, 3.87, 3.87, 4.71	3.34, 4.37, 4.37, 5.43	3.82, 5.08, 5.08, 6.42	4.23, 5.77, 5.77, 7.43	5.00, 6.91, 6.91, 9.00
FO	0.89, 0.92, 0.92, 0.97	1.00, 1.00, 1.00, 1.00	1.02, 1.05, 1.05, 1.10	1.15, 1.21, 1.21, 1.28	1.23, 1.35, 1.35, 1.46	1.43, 1.58, 1.58, 1.74	1.69, 1.90, 1.90, 2.11	2.00, 2.28, 2.28, 2.56	2.20, 2.58, 2.58, 2.96	2.63, 3.11, 3.11, 3.60	2.95, 3.57, 3.57, 4.21	3.24, 4.03, 4.03, 4.86	3.70, 4.69, 4.69, 5.74	4.10, 5.33, 5.33, 6.65	4.84, 6.38, 6.38, 8.05
MH	0.82, 0.88, 0.88, 0.95	0.91, 0.95, 0.95, 0.98	1.00, 1.00, 1.00, 1.00	1.12, 1.15, 1.15, 1.17	1.21, 1.28, 1.28, 1.33	1.40, 1.50, 1.50, 1.59	1.65, 1.80, 1.80, 1.93	1.96, 2.16, 2.16, 2.34	2.16, 2.45, 2.45, 2.70	2.58, 2.95, 2.95, 3.29	2.90, 3.39, 3.39, 3.84	3.18, 3.83, 3.83, 4.43	3.63, 4.45, 4.45, 5.23	3.70, 4.69, 4.69, 5.74	4.75, 6.05, 6.05, 7.34
EQ	0.70, 0.76, 0.76, 0.85	0.78, 0.83, 0.83, 0.87	0.86, 0.87, 0.87, 0.89	1.00, 1.00, 1.00, 1.00	1.08, 1.11, 1.11, 1.14	1.24, 1.31, 1.31, 1.36	1.47, 1.57, 1.57, 1.65	1.74, 1.88, 1.88, 2.00	1.92, 2.13, 2.13, 2.31	2.29, 2.57, 2.57, 2.81	2.58, 2.95, 2.95, 3.29	2.83, 3.33, 3.33, 3.79	3.23, 3.88, 3.88, 4.47	3.57, 4.40, 4.40, 5.18	4.22, 5.27, 5.27, 6.28
EL	0.61, 0.69, 0.69, 0.79	0.68, 0.74, 0.74, 0.81	0.75, 0.78, 0.78, 0.83	0.88, 0.90, 0.90, 0.93	1.00, 1.00, 1.00, 1.00	1.16, 1.18, 1.18, 1.19	1.37, 1.41, 1.41, 1.44	1.62, 1.69, 1.69, 1.75	1.79, 1.91, 1.91, 2.03	2.13, 2.31, 2.31, 2.47	2.39, 2.65, 2.65, 2.88	2.63, 2.99, 2.99, 3.32	3.00, 3.48, 3.48, 3.93	3.32, 3.96, 3.96, 4.55	3.57, 4.40, 4.40, 5.18
ST	0.51, 0.58, 0.58, 0.68	0.57, 0.63, 0.63, 0.70	0.63, 0.67, 0.67, 0.71	0.74, 0.76, 0.76, 0.80	0.84, 0.85, 0.85, 0.86	1.00, 1.00, 1.00, 1.00	1.18, 1.20, 1.20, 1.21	1.40, 1.44, 1.44, 1.47	1.54, 1.63, 1.63, 1.70	1.84, 1.96, 1.96, 2.07	2.07, 2.26, 2.26, 2.42	2.27, 2.55, 2.55, 2.79	2.60, 2.96, 2.96, 3.29	2.87, 3.36, 3.36, 3.81	3.39, 4.03, 4.03, 4.62
TH	0.42, 0.49, 0.49, 0.57	0.47, 0.53, 0.53, 0.59	0.52, 0.56, 0.56, 0.60	0.61, 0.64, 0.64, 0.68	0.69, 0.71, 0.71, 0.73	0.83, 0.83, 0.83, 0.85	1.00, 1.00, 1.00, 1.00	1.18, 1.20, 1.20, 1.21	1.31, 1.36, 1.36, 1.40	1.56, 1.64, 1.64, 1.71	1.75, 1.88, 1.88, 2.00	1.92, 2.13, 2.13, 2.30	2.20, 2.47, 2.47, 2.72	2.43, 2.81, 2.81, 3.15	2.87, 3.36, 3.36, 3.81
VO	0.35, 0.41, 0.41, 0.49	0.39, 0.44, 0.44, 0.50	0.43, 0.46, 0.46, 0.51	0.50, 0.53, 0.53, 0.57	0.57, 0.59, 0.59, 0.62	0.68, 0.70, 0.70, 0.71	0.82, 0.83, 0.83, 0.84	1.00, 1.00, 1.00, 1.00	1.10, 1.13, 1.13, 1.16	1.32, 1.37, 1.37, 1.41	1.48, 1.57, 1.57, 1.64	1.62, 1.77, 1.77, 1.89	1.85, 2.06, 2.06, 2.24	2.05, 2.34, 2.34, 2.59	2.42, 2.80, 2.80, 3.14
EF	0.30, 0.36, 0.36, 0.44	0.34, 0.39, 0.39, 0.45	0.37, 0.41, 0.41, 0.46	0.43, 0.47, 0.47, 0.52	0.49, 0.52, 0.52, 0.56	0.59, 0.61, 0.61, 0.65	0.71, 0.74, 0.74, 0.77	0.87, 0.88, 0.88, 0.91	1.00, 1.00, 1.00, 1.00	1.19, 1.21, 1.21, 1.22	1.34, 1.39, 1.39, 1.42	1.47, 1.56, 1.56, 1.64	1.68, 1.82, 1.82, 1.94	1.86, 2.07, 2.07, 2.24	2.20, 2.48, 2.48, 2.72
ES	0.25, 0.30, 0.30, 0.37	0.28, 0.32, 0.32, 0.38	0.30, 0.34, 0.34, 0.39	0.36, 0.39, 0.39, 0.44	0.41, 0.43, 0.43, 0.47	0.48, 0.51, 0.51, 0.54	0.59, 0.61, 0.61, 0.64	0.71, 0.73, 0.73, 0.76	0.82, 0.83, 0.83, 0.84	1.00, 1.00, 1.00, 1.00	1.12, 1.15, 1.15, 1.17	1.23, 1.30, 1.30, 1.35	1.41, 1.51, 1.51, 1.59	1.56, 1.71, 1.71, 1.84	1.84, 2.05, 2.05, 2.23
RH	0.21, 0.26, 0.26, 0.33	0.24, 0.28, 0.28, 0.34	0.26, 0.29, 0.29, 0.35	0.30, 0.34, 0.34, 0.39	0.35, 0.38, 0.38, 0.42	0.41, 0.44, 0.44, 0.48	0.50, 0.53, 0.53, 0.57	0.61, 0.64, 0.64, 0.68	0.70, 0.72, 0.72, 0.75	0.86, 0.87, 0.87, 0.89	1.00, 1.00, 1.00, 1.00	1.10, 1.13, 1.13, 1.15	1.25, 1.31, 1.31, 1.36	1.39, 1.49, 1.49, 1.58	1.64, 1.79, 1.79, 1.91
CO	0.18, 0.23, 0.23, 0.30	0.21, 0.25, 0.25, 0.31	0.23, 0.26, 0.26, 0.31	0.26, 0.30, 0.30, 0.35	0.30, 0.33, 0.33, 0.38	0.36, 0.39, 0.39, 0.44	0.43, 0.47, 0.47, 0.52	0.53, 0.56, 0.56, 0.62	0.61, 0.64, 0.64, 0.68	0.74, 0.77, 0.77, 0.81	0.87, 0.89, 0.89, 0.91	1.00, 1.00, 1.00, 1.00	1.14, 1.16, 1.16, 1.18	1.26, 1.32, 1.32, 1.37	1.49, 1.58, 1.58, 1.66
EH	0.16, 0.20, 0.20, 0.26	0.17, 0.21, 0.21, 0.27	0.19, 0.22, 0.22, 0.28	0.22, 0.26, 0.26, 0.31	0.25, 0.29, 0.29, 0.33	0.30, 0.34, 0.34, 0.39	0.37, 0.40, 0.40, 0.46	0.45, 0.49, 0.49, 0.54	0.52, 0.55, 0.55, 0.59	0.63, 0.66, 0.66, 0.71	0.73, 0.76, 0.76, 0.80	0.85, 0.86, 0.86, 0.88	1.00, 1.00, 1.00, 1.00	1.11, 1.14, 1.14, 1.16	1.31, 1.36, 1.36, 1.40
CS	0.13, 0.17, 0.17, 0.24	0.15, 0.19, 0.19, 0.24	0.17, 0.21, 0.21, 0.27	0.19, 0.23, 0.23, 0.28	0.22, 0.25, 0.25, 0.30	0.26, 0.30, 0.30, 0.35	0.32, 0.36, 0.36, 0.41	0.39, 0.43, 0.43, 0.49	0.45, 0.48, 0.48, 0.54	0.54, 0.58, 0.58, 0.64	0.63, 0.67, 0.67, 0.72	0.73, 0.76, 0.76, 0.79	0.86, 0.88, 0.88, 0.90	1.00, 1.00, 1.00, 1.00	1.18, 1.20, 1.20, 1.21
NV	0.11, 0.14, 0.14, 0.20	0.12, 0.16, 0.16, 0.21	0.14, 0.17, 0.17, 0.21	0.16, 0.19, 0.19, 0.24	0.19, 0.23, 0.23, 0.28	0.22, 0.25, 0.25, 0.29	0.26, 0.30, 0.30, 0.35	0.32, 0.36, 0.36, 0.41	0.37, 0.40, 0.40, 0.45	0.45, 0.49, 0.49, 0.64	0.52, 0.56, 0.56, 0.61	0.60, 0.63, 0.63, 0.67	0.71, 0.74, 0.74, 0.76	0.83, 0.84, 0.84, 0.85	1.00, 1.00, 1.00, 1.00

$$X_{FH} = \begin{Bmatrix} \sqrt[15]{1 \times 1.03 \times 1.05 \times 1.18 \times \ldots \times 5.00}, \\ \sqrt[15]{1 \times 1.08 \times 1.14 \times 1.31 \times \ldots \times 6.91}, \\ \sqrt[15]{1 \times 1.08 \times 1.14 \times 1.31 \times \ldots \times 6.91}, \\ \sqrt[15]{1 \times 1.12 \times 1.23 \times 1.43 \times \ldots \times 9.00} \end{Bmatrix} = \begin{Bmatrix} 2.039, \\ 2.444, \\ 2.444, \\ 2.836 \end{Bmatrix}$$

$$W_{FH} = \{a_1, b_1, c_1, d_1\} = \begin{Bmatrix} \frac{a_1}{\sum_{j=1}^{15} d_j}, \\ \frac{b_1}{\sum_{j=1}^{15} dc_j}, \\ \frac{c_1}{\sum_{j=1}^{15} b_j}, \\ \frac{d_1}{\sum_{j=1}^{15} a_j} \end{Bmatrix}$$

$$W_{FH} = \begin{Bmatrix} \frac{2.039}{\{2.039+1.964+1.898+\cdots+0.316\}}, \\ \frac{2.444}{\{2.444+2.256+2.131+\cdots+0.355\}}, \\ \frac{2.444}{\{2.444+2.256+2.131+\cdots+0.355\}}, \\ \frac{2.836}{\{2.836+2.551+2.340+\cdots+0.415\}} \end{Bmatrix}$$

By using Equation (5-11), defuzzification is applied to convert to crisp numbers. For example, the weighting factor of falls from height (FH) is as follows:

$$W_{FH} = \left\{ \frac{0.13+2(0.14+0.14)+0.14}{6} \right\} = 0.1352$$

Finally, the total weighting factors of all the safety hazards are obtained according to each criterion and shown in Table 6-16.

Table 6-16: Fuzzy weights of safety hazards

Safety hazards	Fuzzy weights	*WF*
FH	0.13, 0.14, 0.14, 0.14	0.1352
FO	0.12, 0.13, 0.13, 0.13	0.1250
MH	0.12, 0.12, 0.12, 0.12	0.1180
EQ	0.10, 0.10, 0.10, 0.10	0.1032
EL	0.09, 0.09, 0.09, 0.09	0.0925
ST	0.08, 0.08, 0.08, 0.08	0.0791
TH	0.07, 0.07, 0.07, 0.06	0.0661
VO	0.06, 0.06, 0.06, 0.05	0.0551
EF	0.05, 0.05, 0.05, 0.05	0.0487
ES	0.04, 0.04, 0.04, 0.04	0.0403
RH	0.04, 0.04, 0.04, 0.03	0.0352
CO	0.03, 0.03, 0.03, 0.03	0.0312
EH	0.03, 0.03, 0.03, 0.03	0.0268
CS	0.02, 0.02, 0.02, 0.02	0.0238
NV	0.02, 0.02, 0.02, 0.02	0.0199

6.4.4.2 Evaluation of the solutions and determination of the final rank by FTOPSIS

In this step, the evaluation of the fuzzy matrix is completed by estimating the alternatives of subjective judgments. The experts were asked to construct the normalised fuzzy decision matrix by using the linguistic variables presented in Table 6-17. The linguistic terms were converted into corresponding STFN, as shown in Table 6-18, and the aggregated fuzzy evaluation matrix is shown in Table 6-19. It should be noted that due to the limited evaluation, the STFN of PO, SC and PC for FH and FO only are provided here.

Table 6-17: Experts' judgement and corresponding STFN

Input type	Description	Input values	STFN
A numerical value	….is *a*	*a*	(2,2,2,2)
A range of numbers	….is between *a* and *b*	(*a*, *b*)	(2,2,3,3)
A linguistic term 1	….is High	High	(4,4.5,5,6)
A linguistic term 2	….is about *c*	About *c*	(3,4,4,5)
Triangular fuzzy number	….is between *a* and *c* and most likely to be *b*	(*a*, *b* , *c*)	(2,3,3,4)
Trapezoidal fuzzy number	….is between *a* and *d* and most likely to be *b* and *d*	(*a*, *b*, *c*, *d*)	(2,3,4,5)

Table 6-18: Evaluation and STFN of PO, SC and PC

Risk hazards	Experts	Evaluation					
		Probability of occurrence		Severity of consequence		Probability of consequence	
		Score	Converted STFN	Score	Converted STFN	Score	Converted STFN
FH	E_1	2,4	2,2,4,4	4,5	4,4,5,5	3,4	3,3,4,4
	E_2	3	3,3,3,3	5	5,5,5,5	4	4,4,4,4
	E_3	About 4	3,4,4,5	About 4.5	3.5,4.5,4.5,5	About 4.5	3.5,4.5,4.5,5.5
	E_4	4	4,4,4,4	4	4,4,4,4	Likely	2.5,3,4,4.5
	E_5	3,4	3,3,4,4	5	5,5,5,5	4,5,6	4,5,5,6
	Aggregated STFN		2.92, 3.12, 3.77, 3.97		4.28, 4.48, 4.37, 4.83		3.04, 3.83, 4.25, 4.59
FO	E_1	3	2,2,4,4	4,5	4,4,5,5	3,4	3,3,4,4
	E_2	2,4	3,3,3,3	5	5,5,5,5	4	4,4,4,4
	E_3	3,4	3,4,4,5	About 4.5	3.5,4.5,4.5,5	About 4.5	3.5,4.5,4.5,5.5
	E_4	Likely	2,3,3,4	3,4,5	3,4,4,5	4,5,6	4,5,5,6
	E_5	3	3,3.5,4,4.5	Major	3,3.5,4,4.5	Likely	2.5,3,4,4.5
	Aggregated STFN		2.69, 2.77, 3.60, 3.69		2.83, 2.83, 3.57, 3.57		3.15, 3.25, 3.85, 3.95

Table 6-19: Calculation by fuzzification of the STFN of PO, SC and PC

Risk hazards	Probability of occurrence Converted STFN	Severity of consequence Converted STFN	Probability of consequence Converted STFN	Risk = PO×PC×SC
FH	2.92, 3.12, 3.77, 3.97	4.28, 4.48, 4.73, 4.83	3.40, 3.83, 4.25, 4.59	42.43, 53.53, 75.79, 87.92
FO	2.69, 2.77, 3.60, 3.69	2.83, 2.83, 3.57, 3.57	3.15, 3.25, 3.85, 3.95	23.94, 25.48, 49.48, 51.96
MH	2.22, 2.68, 3.75, 4.22	3.10, 3.25, 3.62, 3.77	3.05, 3.30, 3.90, 4.15	20.94, 28.74, 52.94, 65.95
EQ	2.80, 3.05, 3.22, 3.47	2.25, 2.60, 2.60, 2.95	3.17, 3.17, 3.40, 3.40	19.97, 25.14, 28.46, 34.80
EL	2.34, 2.57, 3.39, 3.63	3.77, 3.97, 4.45, 4.65	2.54, 2.77, 3.57, 3.80	22.36, 28.26, 53.86, 64.05
ST	3.33, 3.57, 4.40, 4.65	2.67, 3.15, 3.52, 4.00	2.80, 2.80, 3.40, 3.40	24.86, 31.49, 52.66, 63.17
TH	2.20, 2.37, 2.83, 3.00	2.40, 2.63, 2.88, 3.11	2.63, 2.80, 3.45, 3.62	13.89, 17.45, 28.12, 33.77
VO	2.11, 2.11, 2.11, 2.11	2.14, 2.51, 2.51, 2.88	2.61, 2.61, 2.61, 2.61	11.73, 13.76, 13.76, 15.80
EF	2.74, 3.00, 3.60, 3.87	4.00, 4.37, 4.52, 4.89	2.17, 2.65, 3.05, 3.53	23.74, 34.74, 49.63, 66.72
ES	1.77, 1.77, 1.77, 1.77	3.17, 3.55, 3.55, 3.93	2.47, 2.47, 2.77, 2.77	13.86, 15.52, 17.41, 19.27
RH	2.22, 2.22, 2.22, 2.22	3.30, 3.30, 3.45, 3.45	1.52, 2.32, 2.72, 3.52	11.12, 16.97, 20.80, 26.92
CO	2.58, 2.75, 3.05, 3.22	4.10, 4.10, 4.10, 4.10	1.84, 1.84, 2.30, 2.30	19.44, 20.72, 28.73, 30.33
EH	2.39, 2.81, 3.01, 3.43	2.20, 2.20, 2.84, 2.84	3.04, 3.24, 3.56, 3.76	15.95, 19.99, 30.38, 36.57
CS	2.49, 2.74, 2.74, 2.99	3.28, 3.35, 4.24, 4.32	1.86, 1.98, 2.23, 2.36	15.13, 18.17, 25.91, 30.38
NV	1.58, 2.00, 2.00, 2.42	1.89, 1.97, 3.08, 3.15	1.86, 1.96, 2.16, 2.26	5.54, 7.68, 13.25, 17.19

Using Equation (5-14), the normalised matrix of fuzzy decision is obtained, as illustrated in Table 6-20. The next step is to obtain a fuzzy weighted and normalised decision matrix by utilising weights calculated using the MFAHP. The fuzzy weighted and normalised decision matrix is obtained using Equation (5-15), as shown in Table 6-21.

Table 6-20: Normalised fuzzy decision matrix

Safety hazards	Safety risk = PO×PC×SC
FH	0.4826, 0.6089, 0.8620, 1.0000
FO	0.2722, 0.2898, 0.5628, 0.5910
MH	0.2382, 0.3269, 0.6022, 0.7501
EQ	0.2271, 0.2859, 0.3238, 0.3959
EL	0.2543, 0.3215, 0.6125, 0.7285
ST	0.2827, 0.3581, 0.5989, 0.7185
TH	0.1579, 0.1985, 0.3198, 0.3842
VO	0.1334, 0.1565, 0.1565, 0.1797
EF	0.2700, 0.3951, 0.5645, 0.7588
ES	0.1576, 0.1765, 0.1980, 0.2192
RH	0.1265, 0.1930, 0.2366, 0.3062
CO	0.2211, 0.2357, 0.3267, 0.3449
EH	0.1814, 0.2274, 0.3456, 0.4160
CS	0.1721, 0.2067, 0.2947, 0.3456
NV	0.0630, 0.0874, 0.1507, 0.1955

Based on the STFN presented in Table 6-21, the fuzzy positive ideal solution (A^{+}) by using Equation (5-16) and the fuzzy negative ideal solution (A^{-}) by utilising Equation (5-17) are determined as (0.0652, 0.0823, 0.1165, 0.1352) and (0.0013, 0.0017, 0.0030, 0.0039) respectively. Then, the distance of each risk from the fuzzy positive ideal solution (d^{+}) and the fuzzy negative ideal solution (d^{-}) is computed using Equations (5-18) and (5-19) respectively. Finally, a preference order can be ranked according to Equation (5-20) and the order of the CC_i^* index, as shown in Table 6-22.

Table 6-21: Weighted normalised fuzzy decision matrix

Safety hazards	Safety risk = PO×PC×SC
FH	0.0652, 0.0823, 0.1165, 0.1352
FO	0.0340, 0.0362, 0.0704, 0.0739
MH	0.0281, 0.0386, 0.0710, 0.0885
EQ	0.0234, 0.0295, 0.0334, 0.0409
EL	0.0235, 0.0297, 0.0567, 0.0674
ST	0.0224, 0.0283, 0.0474, 0.0568
TH	0.0104, 0.0131, 0.0211, 0.0254
VO	0.0073, 0.0086, 0.0086, 0.0099
EF	0.0131, 0.0192, 0.0275, 0.0369
ES	0.0064, 0.0071, 0.0080, 0.0088
RH	0.0044, 0.0068, 0.0083, 0.0108
CO	0.0069, 0.0074, 0.0102, 0.0108
EH	0.0049, 0.0061, 0.0093, 0.0112
CS	0.0041, 0.0049, 0.0070, 0.0082
NV	0.0013, 0.0017, 0.0030, 0.0039

For example, the fuzzy positive ideal solution (d^+) of FO is as follows:

$$d_i^+ = \sqrt{(0.034-0.065)^2 + (0.036-0.082)^2 + (0.070-0.116)^2 + (0.073-0.135)^2}$$

$$d_i^+ of FO = 0.0948$$

$$d_i^- = \sqrt{(0.034-0.001)^2 + (0.036-0.001)^2 + (0.070-0.003)^2 + (0.073-0.003)^2}$$

$$d_i^- of FO = 0.1082$$

Finally, a preference order can be ranked according to the order of the CC_i^* index using Equation (17), as shown in Table 6-22.

For example, the order of the CC_i^* index of FO is as follows:

$$CC_i^* of FO = \frac{(0.1082)}{(0.1082 + 0.0948)} = 0.5330$$

The same procedure can be used to compute the distances, as shown in Table 6-22.

Table 6-22: Calculation of the fuzzy closeness coefficient for each risk

Risk hazards	Description	d^+	d^-	CC_i^*	Rank
FH	Falls from height	0.0000	0.2017	1.0000	1
FO	Falling objects	0.0948	0.1082	0.5330	3
MH	Manual handling	0.0868	0.1177	0.5754	2
EQ	Equipment, machinery and tools	0.1426	0.0596	0.2948	6
EL	Electricity	0.1126	0.0905	0.4454	4
ST	Slips and trips	0.1252	0.0770	0.3807	5
TH	Traffic hazards	0.1701	0.0317	0.1569	8
VO	Vehicle overturn	0.1900	0.0123	0.0608	10
EF	Fire and explosions	0.1558	0.0462	0.2288	7
ES	Exposure to hazardous substances	0.1920	0.0102	0.0504	13
RH	Radiation hazards	0.1913	0.0105	0.0521	12
CO	Collapse of site structure	0.1892	0.0127	0.0629	9
EH	Ergonomic/human factors	0.1906	0.0111	0.0551	11
CS	Confined spaces	0.1945	0.0072	0.0359	14
NV	Noise and vibration	0.2017	0.0000	0.0000	15

The final results are summarised based on the closeness coefficient (CC_i^*) values ranked in descending order : FH > MH > FO > EL > ST > EQ > EF > TH > CO > VO > EH > RH > ES > CS > NV. The next step is the control of safety risks, which will be addressed in the next section.

6.4.3 Safety Risk Control and Monitoring

According to the results obtained, falls from height (FH) is one of the most dangerous hazard groups. Common cases of work at height injuries are falls from scaffolding and ladders and through fragile roofs. Falls from height are currently defined as one of the biggest single causes of worker deaths and major injuries on construction sites (Wong et al., 2016). This includes using platforms such as fixed scaffolding, mobile scaffold towers, scissor lifts, podium platforms, cherry pickers, and moveable platforms and roof work, floors, fragile surfaces, hole in the ground, and using fixed ladders or stepladders. Wong et al (2016) state that the number of scaffolding accidents has the highest frequency of falls, as scaffolders spend more time working at height than the other trades.

The work at height regulations proposed by the HSE recommend avoiding the need to work at height whenever possible, for example, by using vehicles with automated or manual systems that enable loads to be sheeted safely from the ground. On the other hand, if working at height cannot be avoided, should be ensured that proper planning and supervision is undertaken so that the work can be carried out as safely as is reasonably practicable. Lone working must be avoided, emergencies and rescue manuals should be appropriately planned. The places of work are also a consideration, and potential hazards such as high-risk areas and fragile roofs must be taken into consideration. Equipment such as work platforms, scaffolding and stepladders must be appropriate for the job, built and maintained safely, inspected, tested, and dismantled appropriately. Safety inspections should be undertaken regularly by a competent person and documented, and faulty equipment should be repaired or disposed of as necessary (HSE, 2011).

All site project equipment should be appropriate with working at height protection and suitable for safety protection where necessary (HSE, 2011). PPE should be utilised with the other safety protection equipment to prevent the residual risk remaining within an intolerable level. Site project staff should be well trained and qualified to cope with difficulties in dealing with safety measures regarding site equipment and features. The site equipment should be regularly inspected depending on the safety situation awareness on site, and staff profiles should be reviewed every six months as a minimum to suggest any useful ideas and recommendations (HSE, 2011).

6.5 Summary

The proposed construction safety risk management model using the FRT, MFAHP and FTOPSIS methods was established to assess both qualitative and quantitative safety risk data. Three parameters (PO, SC and PC) were employed in the proposed model to obtain and improve reliability and accuracy outcomes of safety risk analysis. This newly developed safety risk management model can be used to obtain both a safety risk level and categories of safety risk with a degree of confidence and a final safety ranking for evaluating important safety risks in the construction projects. Four case studies will be presented in the next chapter to demonstrate the proposed safety risk management model application.

CHAPTER SEVEN

CASE STUDIES

7.1 Introduction

This chapter presents case studies on safety risk assessment and management in building and mass rapid transit railway construction projects, which are used to illustrate the developed safety risk assessment and management methodology, including an evaluation of important safety risks using the FRT, FAHP, and FTOPSIS methods which have been incorporated into the model. The case study materials were collected from the particular construction projects in Thailand: CH Karnchang PCL, Syntec Construction PCL, Sangfah Construction and Engineering Co. Ltd and Bouygues- Thai Ltd. The results of the safety risk assessment are safety risk scores for overall project, hazard groups, hazardous events, and types of safety risk with a confidence percentage. Then, each hazard group is assessed and prioritised by using the FRT, MFAHP and FTOPSIS methods to obtain the safety risk ranking from the highest importance to the lowest importance. Finally, discussion and the decision-making process based on controlling, mitigating, and monitoring risk hazards is provided. Some key parts of this chapter incorporate content from a conference publication jointly by the author (Sansakorn and An, 2015).

7.2 Case Study 1: Building Construction Project

7.2.1 Background of Case Study 1

"Building Construction Company 1" is used instead of the building construction company's name due to business confidentiality. The company provides various types of services, including structural and architectural works; infrastructure works; civil engineering; design;

consultancy and management; mechanical and electrical engineering services; piling and foundation engineering services and retrofitting; and refurbishment services. This construction project is a condominium project in Bangkok, Thailand. The condominium comprises a single building with 38 floors and 802 units.

7.2.2 Establishing a Safety Risk Management Team

To order to analyse safety risks related with a project of the building construction, six experts involved in the development of the safety risk management model were selected based on their individual skills, knowledge, experience, and expertise. One is a project manager who had worked on building construction projects for more than 35 years. Two experts are projects engineers with 15 years' experience in working on building construction projects. The other three experts are a senior safety officer, a safety officer, and a site superintendent, as shown in Table 7-1.

Table 7-1: Description of experts' contribution factor

Expert	Title of expert	Score	Years of experience	Score	Weighting score	Weighting factor
Expert 1	Project Manager	5	35	5	10	0.20
Expert 2	Senior Safety Officer	4	40	5	9	0.18
Expert 3	Project Engineer	4	15	5	9	0.18
Expert 4	Project Engineer	4	15	5	9	0.18
Expert 5	Site superintendent	3	25	5	8	0.16
Expert 6	Safety Officer	2	5	3	5	0.10

7.2.3 Safety Hazard Identification

To carry out safety risk assessment and management, the safety risk management team of the building construction project verified to contain all the hazard groups and hazardous events by brainstorming and discussions. The building construction safety system is divided into 14 hazard groups: falls from height; falling objects; manual handling; equipment machinery and tools; electricity; slips and trips; traffic hazards; vehicle overturn; fire and explosions; exposure to hazardous substances; collapse of site structure; confined space; ergonomic/ human factors; and noise and vibration. Each hazard group includes several identified and codified risk events, which are described below and in Figure 7-1.

(1) *Falls from height* includes eight hazardous events: working platform (FH-01), placement ladder (FH-02,) erection of scaffolding (FH-03), climbing cranes (FH-04), temporary ladder (FH-05), hole in the ground (FH-06), working on height unprotected (FH-07), and through opening elevator shaft (FH-08).

(2) *Falling objects* includes seven hazardous events: part of climbing cranes, scaffolds (FO-09), operating, cleaning and clearing (FO-10), blown by wind (FO-11), hand-held tools (FO-12), hopper and bucket (FO-13), stacked items (FO-14), and objects under pressure or tension (FO-15).

(3) *Manual handling* includes two hazardous events: hoists (MH-16) and mobile crane lifting (MH-17).

(4) *Equipment, machinery and tools* includes three hazardous events: heavy equipment (EQ-18), steel bar bending machine (EQ-19), and vibrator machine (EQ-20).

(5) *Electricity* includes four hazardous events: wires (EL-21), electrical work (EL-22), overhead power lines (EL-23), and arc welding machine (EL-24).

(6) *Slips and trips* includes five hazardous events: tripping over building materials (ST-25), slipping on wet surfaces (ST-26), trips caused by small change in level (ST-27),

trips caused by water pipes, rebar (ST-28), and walking around construction site (ST-29).

(7) *Traffic hazards* includes two hazardous events: collision with another vehicle (TH-30) and collision with plant/people (TH-31).

(8) *Vehicle overturn* includes two hazardous events: crane overturn (VO-32) and mobile plant (Bobcats, tractor) (VO-33).

(9) *Fire and explosions* includes four hazardous events: hot work (FE-34), working near flammables (FE-35), gas cylinder or hose leakage (FE-36), and fire extinguisher has been discharged (FE-37).

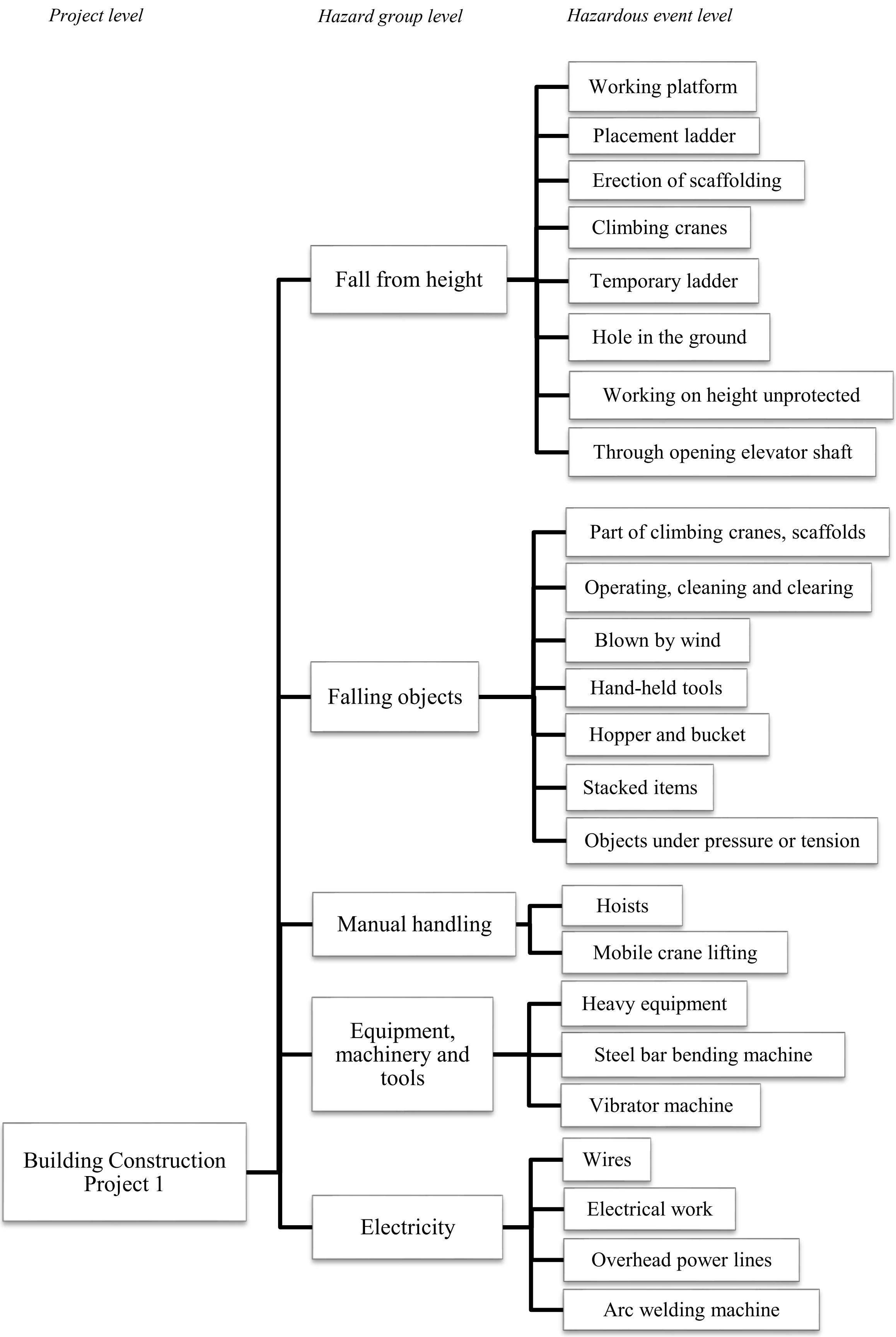
(10) *Exposure to hazardous substances* includes three safety hazardous events, i.e. solvents (ES-38), cement dust (ES-39), corrosive substances (ES-40).

(11) *Collapse of site structure* includes five hazardous events: collapse of boom (cranes) (CO-41), collapse of scaffolding (CO-42), temporary structure (CO-43), steel sheet piles (CO-44), and kingpost (CO-45).

(12) *Confined space* includes two hazardous events: deep excavations (CS-46) and closed tanks (CS-47).

(13) *Ergonomic and human factors* includes three hazardous events: poor work posture (EH-48), repetitive movement (EH-49), and extreme muscular exertion (EH-50).

(14) *Noise and vibration* includes five hazardous events: piling (NV-51), excavation (NV-52), hammering (NV-53), vibrator machine (NV-54), and hand-held power tools (NV-55).


Project level
Hazard group level
Hazardous event level
Building Construction Project 1
Fall from height
Working platform
Placement ladder
Erection of scaffolding
Climbing cranes
Temporary ladder
Hole in the ground
Working on height unprotected
Through opening elevator shaft
Falling objects
Part of climbing cranes, scaffolds
Operating, cleaning and clearing
Blown by wind
Hand-held tools
Hopper and bucket
Stacked items
Objects under pressure or tension
Manual handling
Hoists
Mobile crane lifting
Equipment, machinery and tools
Heavy equipment
Steel bar bending machine
Vibrator machine
Electricity
Wires
Electrical work
Overhead power lines
Arc welding machine

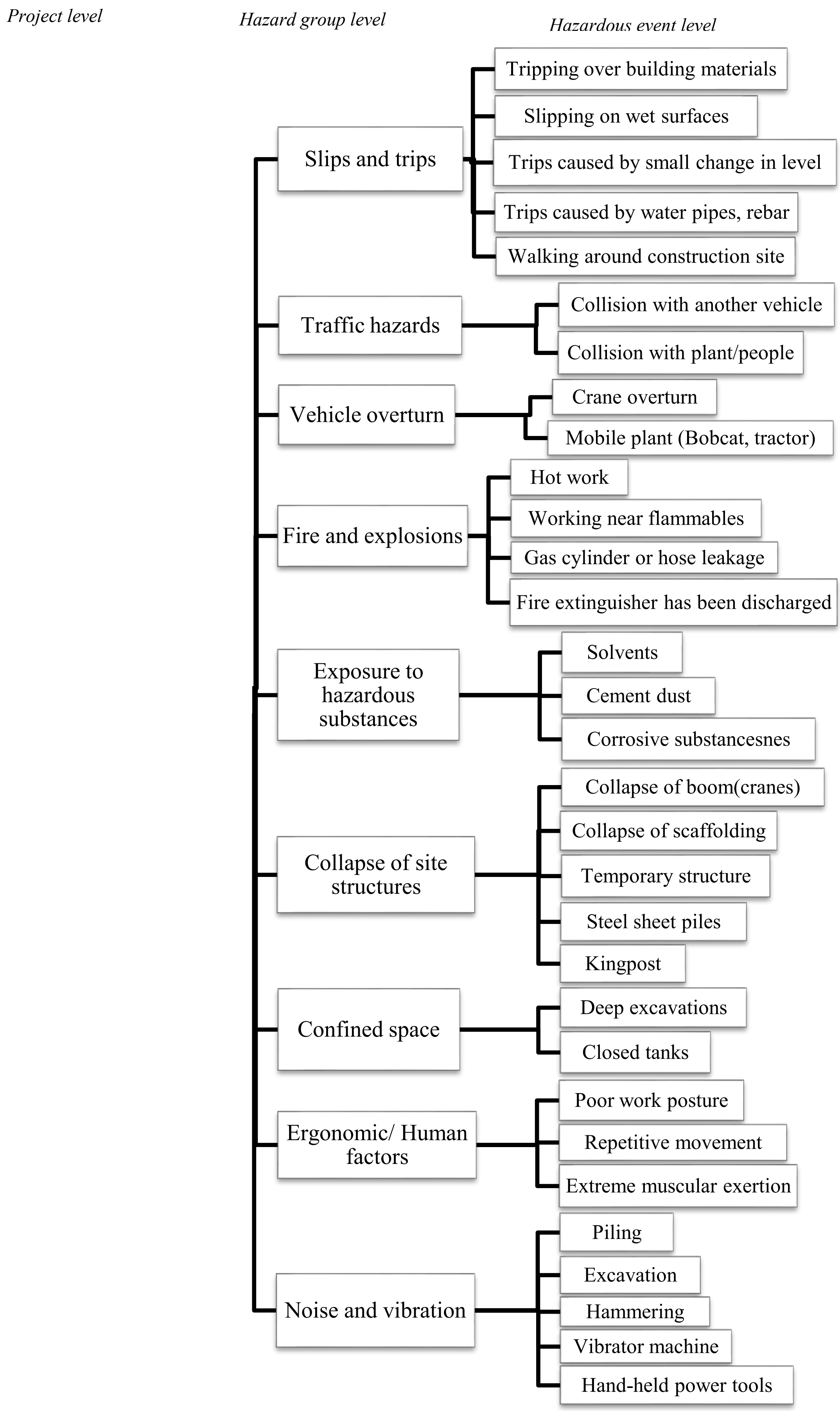


Figure 7-1: Hazard identification at building construction project 1

7.2.4 Establishment of Safety Risk Criteria

7.2.4.1 Determining the safety risk parameters and fuzzy membership functions (MF_f)

(Sansakorn and An, 2015)

In this case study, the three fundamental risk parameters, probability of occurrence (PO), and severity of consequence (SC), and probability of consequence (PC), were adopted and form the basis for the questions put to the experts. Five linguistic variables of probability of occurrence (PO), which refers to the number of times an event occurs or the failure frequencies in a certain time period are suggested "*Very unlikely*", "*Unlikely*", "*Fairly unlikely*", "*Likely*", and "*Very likely*" as shown in Table 7-2.

Table 7-2: Definitions of PO of building construction project 1

Qualitative descriptors	Description	Range
Very unlikely	Failure is unlikely but possible during lifetime	0.0-1.0
Unlikely	Likely to happen once during lifetime	0.5-2.0
Fairly unlikely	Between unlikely and likely	1.5-3.5
Likely	Occasional failure	3.0-4.5
Very likely	Failure is almost unavoidable	4.0-5.0

Source: Sansakorn and An, 2015

The trapezoidal membership functions (MF_f) are applied to describe these linguistic variables, as shown in Figure 7-3.

Severity of consequence (SC) refers to the number of minor injuries, major injuries and fatalities resulting from the occurrence of a particular event, for which the five linguistic variables are: "*Negligible*", "*Minor*", "*Moderate*", "*Major*", and "*Catastrophic*", which represent no injury, minor injuries and/or <3 days off work, multiple injuries and/or between 3 days and 1 month off work, severe injuries and/or >1 month off work, and fatality and/or large number of fatal injuries respectively, as shown in Table 7-3.

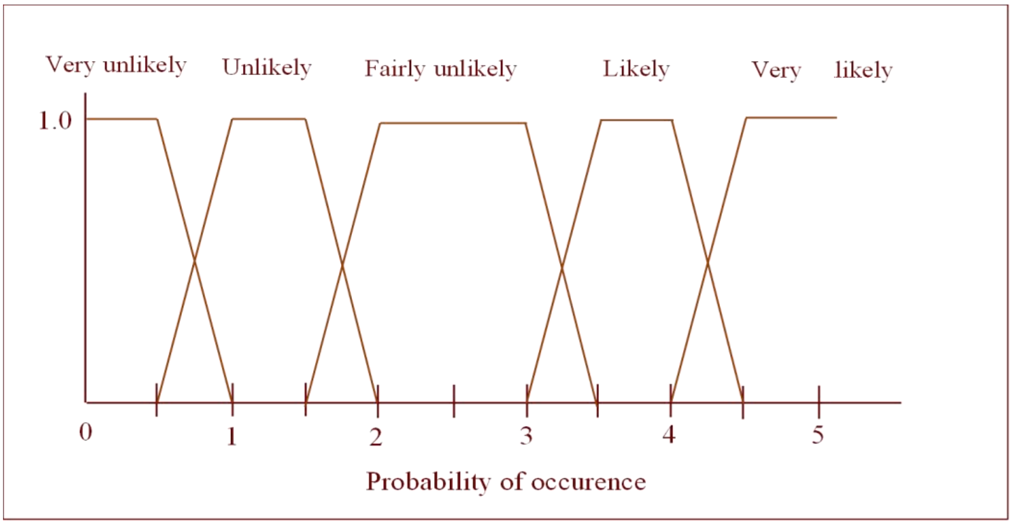


Figure 7-2 Fuzzy PO of MF_f of building construction project 1

Table 7-3: Definitions of SC of building construction project 1

Qualitative descriptors	Description	Range
Negligible	No injury	0.0-1.0
Minor	Minor injuries and/or <3 days off work	0.5-2.0
Moderate	Multiple injuries and/or between 3 days and 1 month off work	1.5-3.5
Major	Severe injuries and/or >1 month off work	3.0-4.5
Catastrophic	Fatality and/or large number of fatal injuries	4.0-5.0

The linguistic variables "*Negligible*", "*Minor*", "*Moderate*", "*Major*", and "*Catastrophic*", are defined by the trapezoidal membership functions as shown in Figure 7-3.

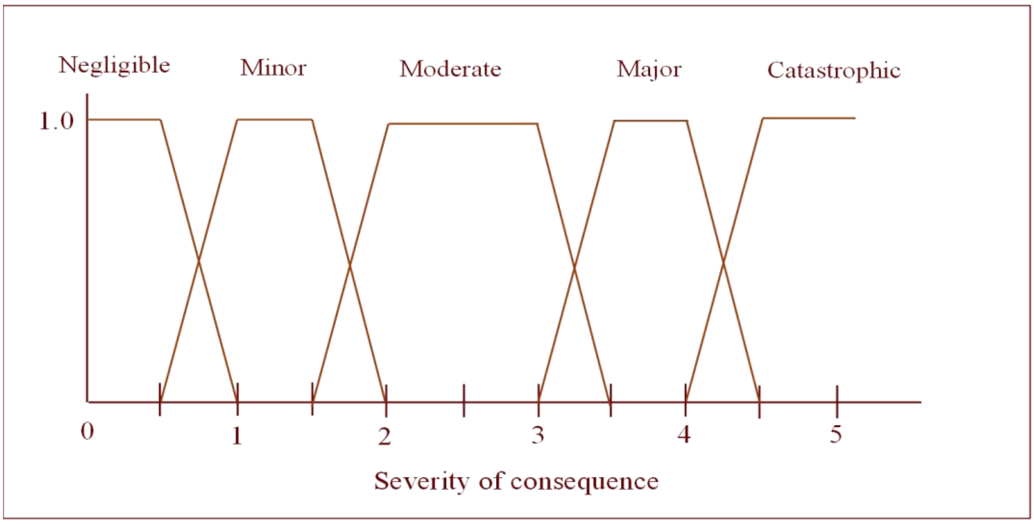


Figure 7-3: Fuzzy SC of MF_f of building construction project 1

Probability of consequence (PC) is a new parameter which refers to the likelihood of accident occurrence if an event becomes a reality, Six linguistic variables are used in this research to describe PC "*Highly unlikely*", "*Unlikely*", "*Reasonably unlikely*", "*Likely*", "*Reasonably likely*", and "*Highly likely*" as shown in Table 7-4.

Table 7-4: Definitions of PC of building construction project 1

Qualitative descriptors	Description	Range
Highly unlikely	The probability of accident occurrence is highly unlikely	0.0-1.0
Unlikely	The probability of accident occurrence is unlikely but the failure event could occur	0.5-2.0
Reasonably unlikely	The probability of accident occurrence is between unlikely and likely	1.5-3.0
Likely	The probability of accident occurrence is likely	2.5-4.5
Reasonably likely	The probability of accident occurrence is between likely and highly likely	4.0-5.5
Highly likely	The probability of accident occurrence is very likely	5.0-6.0

Similarly, the trapezoidal membership functions (MF_f) of PC are determined to describe these linguistic terms, as shown in Figure 7-4.

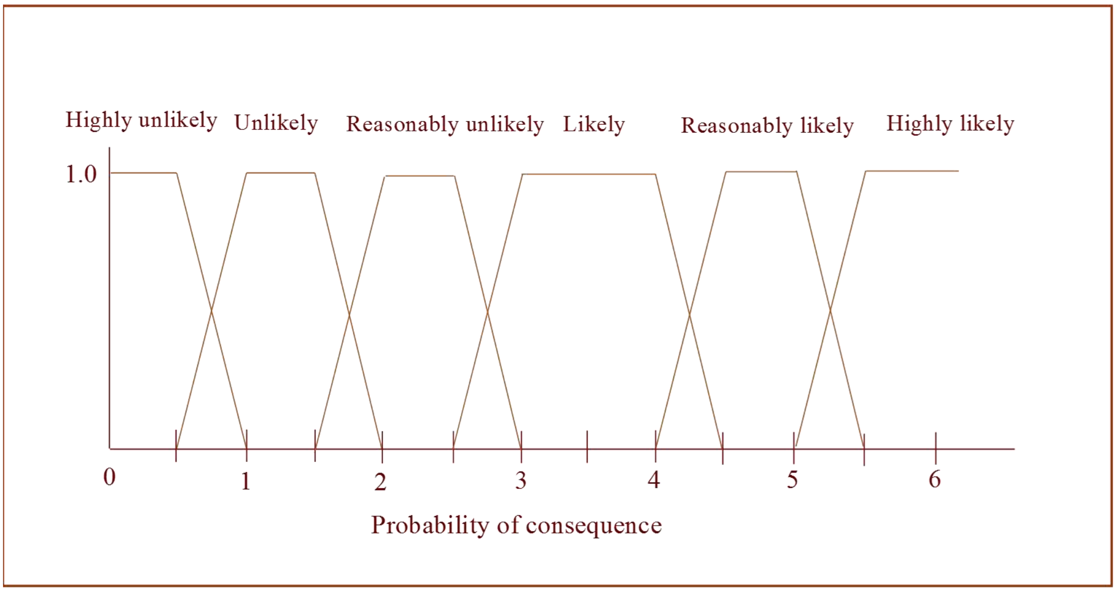


Figure 7-4: Fuzzy PC of MF_f of building construction project 1

The risk magnitude (RM) is defined in terms of the linguistic variables, "*Low*", "*Acceptable*", "*Average*", "*High*", and "*Unacceptable*", where the highest score is 5 and the lowest score is 0, with the safety risk ranging from 4 to 5 defined as "*Unacceptable*". These definitions are generally similar to those in the occupational health and safety management regulations published by the HSE, as shown in Table 7-5.

The linguistic variables, "*Low*", "*Acceptable*", "*Average*", "*High*", and "*Unacceptable*" are defined by the trapezoidal membership functions, as shown in Figure 7-5.

Table 7-5: Definitions of RM of building construction project 1

Qualitative descriptors	Description	Range
Low	Risk is low or insignificant and can be readily controlled	0.0-1.0
Acceptable	Risk is acceptable	0.5-2.0
Average	Risk is medium	1.5-3.5
High	Risk is high; however, risk control should be undertaken if it is reasonably practicable to so	3.0-4.5
Unacceptable	Risk is unacceptable. Proper action must be taken to eliminate or reduce the risk	4.0-5.0

Source: Sansakorn and An, 2015

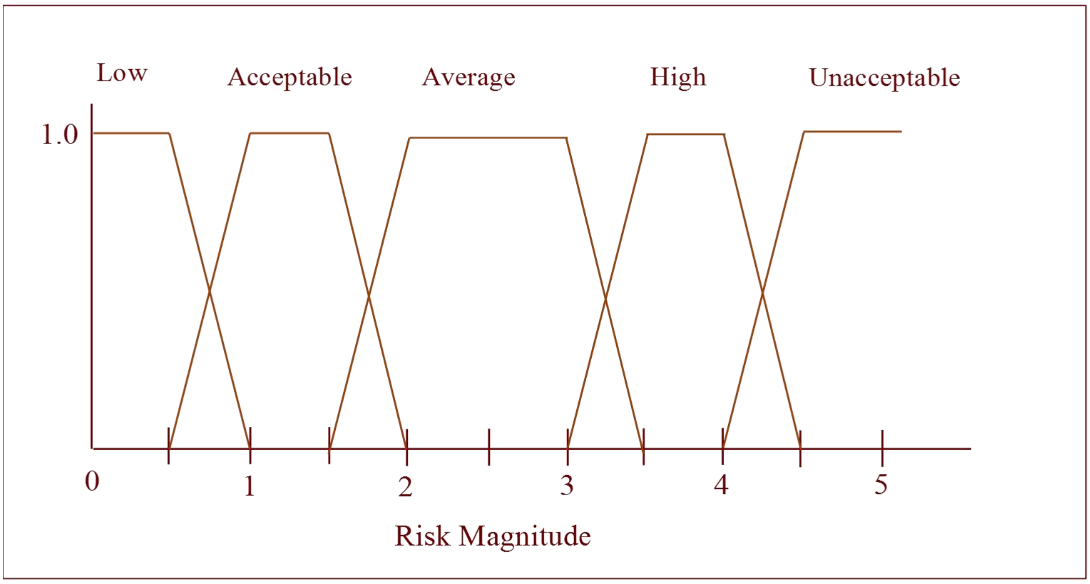


Figure 7-5: Fuzzy RM of MF_f of building construction project 1

7.2.4.2 Establishment of fuzzy rule base

In this case, experts' judgement and knowledge are used to derive the fuzzy rules, and five linguistic variables of PO and SC and six of PC are employed to determine the safety risk magnitude of the hazardous events, hazard groups, and all systems. Therefore, a rule base comprising 150 (5 × 5 × 6) if-then rules is developed which is shown in Figure 7-6.

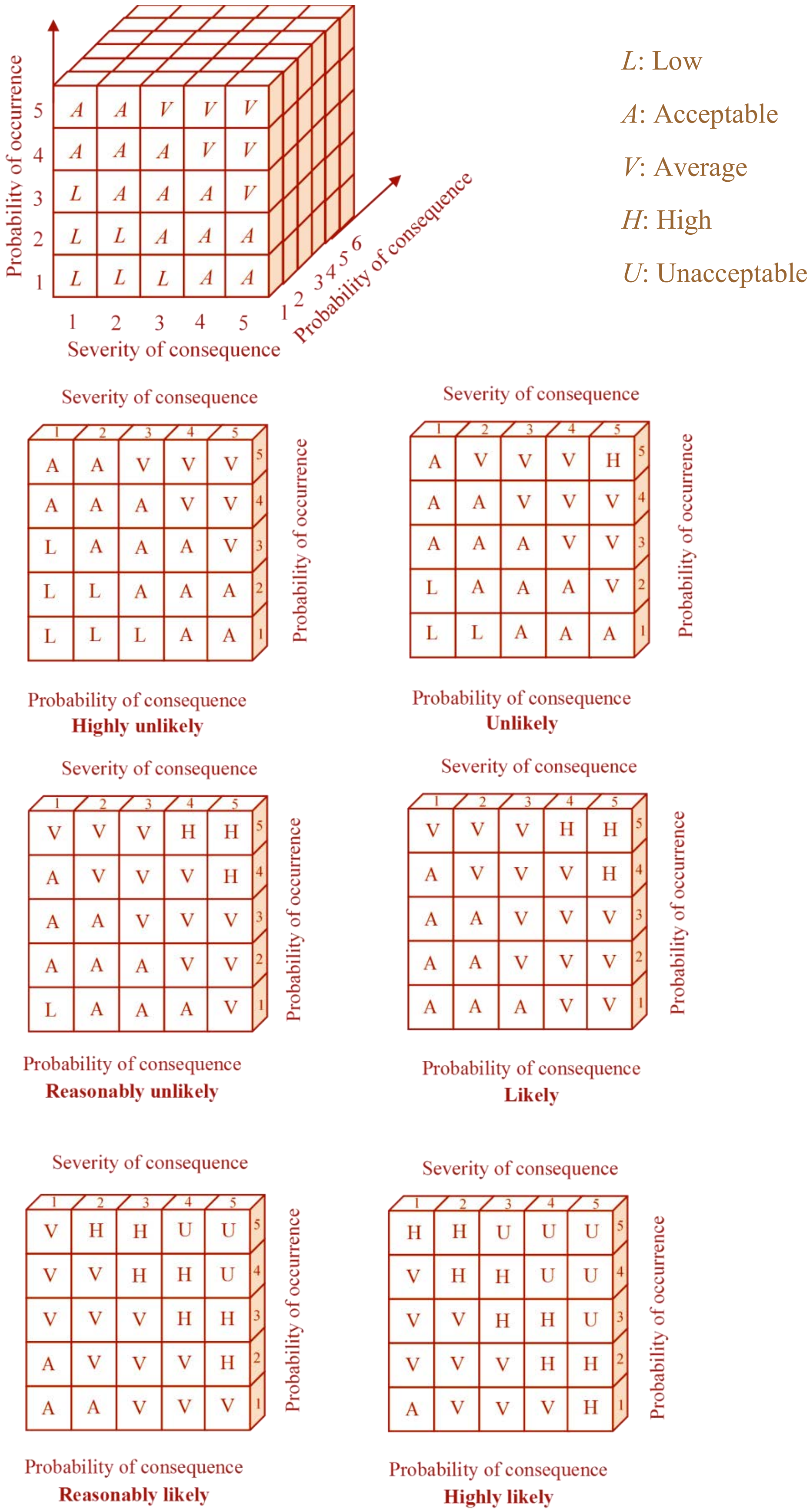


Figure 7-6: Fuzzy sliced cubic rule bases of building construction project 1

For example, the rule at the bottom right of the fuzzy sliced cubic rule base of "Highly likely" would be described as "IF PO is *Very likely* and SC is *Catastrophic* and PC is *Highly likely,* THEN RM is *Unacceptable"* or "IF PO is *Very unlikely* and SC is still *Catastrophic* and PC is *Highly likely,* THEN RM is *High*".

7.2.5 Input PO, SC and PC

Once the safety risk parameters and MF_f have been determined, the data on PO, SC and PC is obtained from the experts. For example, it can be seen that Experts E_{1-4} use numerical values, E_5 provides a range of numbers in PO, a triangular fuzzy number in SC, and a numerical value in PC, while E_6 uses numerical values in PO and PC and a range of numbers in SC to describe the hazardous event of working platform (FH-01) in building construction project 1, as shown in Table 7-6.

Table 7-6: Evaluation and STFN of PO, SC, and PC (FH-01)

Experts	Evaluation					
	Probability of occurrence		Severity of consequence		Probability of consequence	
	Score	Converted STFN	Score	Converted STFN	Score	Converted STFN
E_1(0.20)	2	(2,2,2,2)	3	(3,3,3,3)	3	(3,3,3,3)
E_2(0.18)	2	(2,2,2,2)	1	(1,1,1,1)	3	(3,3,3,3)
E_3(0.18)	3	(3,3,3,3)	5	(5,5,5,5)	5	(5,5,5,5)
E_4(0.18)	1	(1,1,1,1)	5	(5,5,5,5)	3	(3,3,3,3)
E_5(0.16)	(1,2)	(1,1,2,2)	(3,4,5)	(3,4,4,5)	1	(1,1,1,1)
E_6(0.10)	2	(2,2,2,2)	(1,2)	(1,1,2,2)	3	(3,3,3,3)
Aggregated STFN	(1.84,1.84, 2.00,2.00)		(3.16, 3.32, 3.42, 3.58)		(3.04, 3.04, 3.04, 3.04)	

7.2.6 Fuzzy Aggregation

The aggregations of PO of FH-01 scores can be calculated:

$$\text{Probability of occurrence } \mu(x)$$
$$= \big((2,2,2,2) \times 0.20 + (2,2,2,2) \times 0.18 + (3,3,3,3) \times 0.18$$
$$+ (1,1,1,1) \times 0.18 + (1,1,2,2) \times 0.16 + (2,2,2,2) \times 0.10\big)$$
$$= (1.84,\ 1.84,\ 2.00,\ 2.00)$$

$$\text{Probability of occurrence } \mu(x) = (1.84,\ 1.84,\ 2.00,\ 2.00)$$

Similarly,

$$\text{Severity of occurrence } \mu(x) = (3.16, 3.32, 3.42, 3.58)$$
$$\text{Probability of consequence } \mu(x) = (3.04, 3.04, 3.04, 3.04)$$

The obtained results of risk parameters are shown in Table 7-7.

7.2.7 Fuzzy Inference (Sansakorn and An, 2015)

This step is to convert the aggregation of PO, SC and PC into matching fuzzy sets for fuzzy inference. For example, the aggregated STFN of PO of FH-01 = $(1.84,\ 1.84,\ 2.00,\ 2.00)$, as shown in Figure 7-7 (the thick segments), and the matching fuzzy set PO is obtained by intersections between the STFN and fuzzy sets of PO:

$$PO = \{(Unlikely,\ 0.32),\ (Fairly\ unlikely,\ 1.000)$$

Similarly, the matching fuzzy sets of SC and PC of FH-01 are

$$PC = \{(Likely,\ 0.80),\ (Reasonably\ unlikely,\ 0.92)\}$$
$$SC = \{(Moderate,\ 0.52),\ (Major,\ 1.000)\}$$

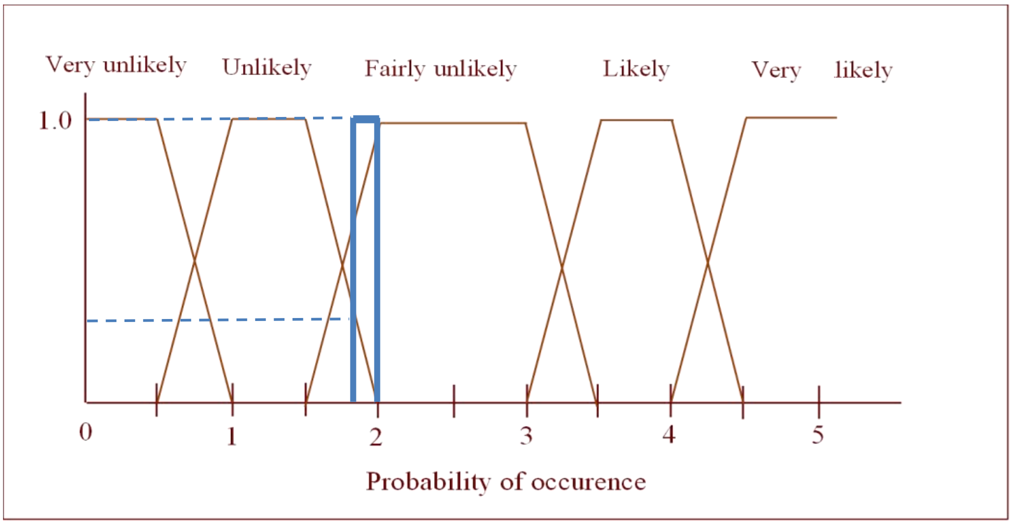


Figure 7-7: Fuzzy PO of MF_f of building construction project 1

The min-max implication is then employed to calculate the fuzzy preference. The fuzzy inference can be broken down into four phases, as described below.

Stage 1 is to determine which rules are in the rule base. From the mapping of inputs of *PO*×*SC*×*PC*, the following eight rules are developed, contributing to the evaluation process.

Rule#69:IF PO is Unlikely and SC is Moderate and PC is Reasonably unlikely, THEN RM is Acceptable

Rule#70:IF PO is Unlikely and SC is Moderate and PC is Likely, THEN RM is Average

Rule#99:IF PO is Unlikely and SC is Major and PC is Reasonably unlikely, THEN RM is Average

Rule#100:IF PO is Unlikely and SC is Major and PC is Likely, THEN RM is Average

Rule#75:IF PO is Fairly unlikely and SC is Moderate and PC is Reasonably unlikely, THEN RM is Average

Rule#76:IF PO is Fairly unlikely and SC is Moderate and PC is Likely, THEN RM is Average

Rule #105:IF PO is Fairly unlikely and SC is Major and PC is Reasonably unlikely, THEN RM is Average

Rule #106:IF PO is Fairly unlikely and SC is Major and PC is Likely, THEN RM is Average

Stage 2 is to apply the minimum operator to calculate the strength of the fired rules, this process is as follows:

- $Rule$ #69: $\alpha_{69} = \mu UN(PO) \cap \mu MO(SC) \cap \mu RU(PC) = min(0.32, 0.52, 0.92) = 0.32$
- $Rule$ #70: $\alpha_{70} = \mu UN(PO) \cap \mu MO(SC) \cap \mu LI(PC) = min(0.32, 0.52, 0.08) = 0.08$
- $Rule$ #75: $\alpha_{75} = \mu FU(PO) \cap \mu MO(SC) \cap \mu RU(PC) = min(1.00, 0.52, 0.92) = 0.52$
- $Rule$ #76: $\alpha_{76} = \mu FU(PO) \cap \mu MO(SC) \cap \mu LI(PC) = min(1.00, 0.52, 0.08) = 0.08$
- $Rule$ #99: $\alpha_{99} = \mu UN(PO) \cap \mu MA(SC) \cap \mu RU(PC) = min(0.32, 1.00, 0.92) = 0.32$
- $Rule$ #100: $\alpha_{100} = \mu UN(PO) \cap \mu MA(SC) \cap \mu LI(PC) = min(0.32, 1.00, 0.08) = 0.08$
- $Rule$ #105: $\alpha_{105} = \mu FU(PO) \cap \mu MA(SC) \cap \mu RU(PC) = min(1.00, 1.00, 0.92) = 0.92$
- $Rule$ #106: $\alpha_{106} = \mu FU(PO) \cap \mu MA(SC) \cap \mu LI(PC) = min(1.00, 1.00, 0.08) = 0.08$

where UN_{PO} and FU_{PO}, are the qualitative descriptors "*Unlikely*" and "*Fairly unlikely*" of PO, respectively, MO_{SC}, MA_{SC} are the qualitative descriptors "*Moderate*" and "*Major*" of SC respectively, and RU_{PC} *and* LI_{PC}, are the qualitative descriptors "*Reasonably unlikely*" and "*Likely*" of PC respectively.

Stage 3 is to determine the control fired rules in outputs:

- $Rule$ #69: $\alpha_{69} \cap \mu A(RM) = min(0.32, \mu A(RM))$
- $Rule$ #70: $\alpha_{70} \cap \mu V(RM) = min(0.08, \mu V(RM))$
- $Rule$ #75: $\alpha_{75} \cap \mu V(RM) = min(0.32, \mu V(RM))$
- $Rule$ #76: $\alpha_{76} \cap \mu V(RM) = min(0.08, \mu V(RM))$
- $Rule$ #99: $\alpha_{99} \cap \mu V(RM) = min(0.52, \mu V(RM))$
- $Rule$ #100: $\alpha_{100} \cap \mu V(RM) = min(0.08, \mu V(RM))$
- $Rule$ #105: $\alpha_{105} \cap \mu V(RM) = min(0.92, \mu V(RM))$
- $Rule$ #106: $\alpha_{106} \cap \mu V(RM) = min(0.08, \mu V(RM))$

It should be noted that the following rules, *Rule* #70, *Rule* #75, *Rule* #76, *Rule* #99, *Rule* #100 and *Rule* #106, are included in *Rule* #105.

The maximum operator is taken to calculate

$\mu Q_{RM}(x) = \max\{\min(0.32,\ \mu A(RM)),\ \min(0.92,\ \mu V(RM))\}$

7.2.8 Defuzzification

The fuzzy output RM can be defuzzified by Equation (6-12) based on the centre-average defuzzification. The safety risk magnitude of the hazardous event FH-01 is obtained as RM = 2.61, which illustrates the risk level within RM axis, as shown in Figure 7-8.

$$RM_{FH\text{-}01} = \frac{1.5\times0.32+3\times0.92}{0.32+0.92} = 2.61$$

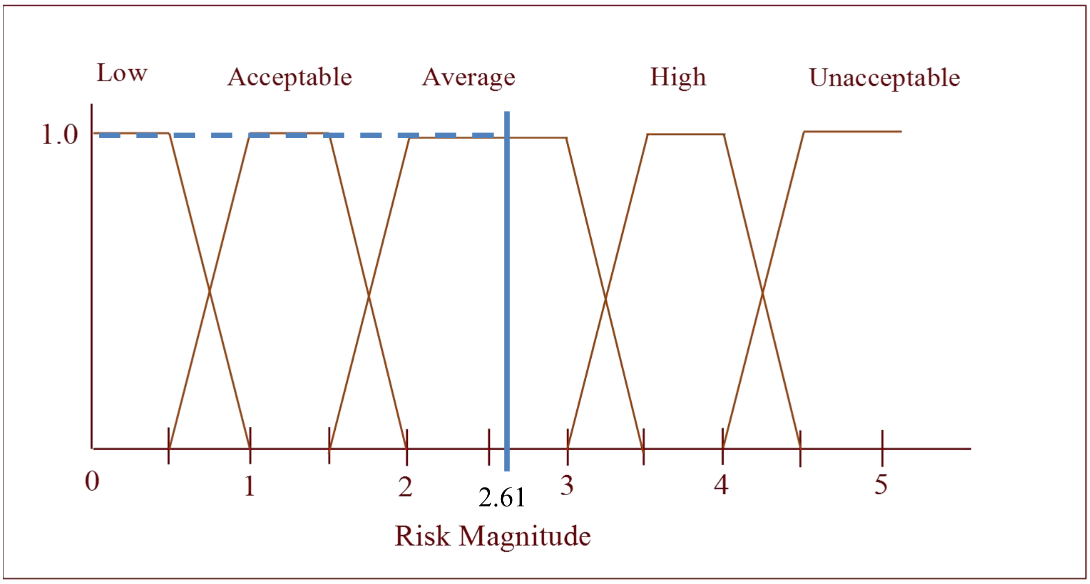


Figure 7-8: Risk magnitude of MF_f of FH-01 in building construction project 1

By following the eight steps above, the safety risk magnitude of all the hazardous events of building construction project 1 are computed, and the results are shown in Table 7-7

Table 7-7: Safety risk magnitude of building construction project 1

Hazard Groups	Hazardous events	Probability of occurrence	Aggregated STFN Severity of consequence	Probability of consequence	Safety risk scores	Safety risk categories
Falls from height	FH-01 Working platform	1.84, 1.84, 2.00, 2.00	3.16, 3.32, 3.42, 3.58	3.04, 3.04, 3.04, 3.04	2.61	Average: 100%
	FH-02 Placement ladder	1.94, 1.94, 1.94, 1.94	2.84, 2.84, 2.94, 2.94	3.24, 3.24, 3.24, 3.24	2.72	Average: 100%
	FH-03 Erection of scaffolding	2.00, 2.00, 2.16, 2.16	2.84, 2.84, 2.94, 2.94	2.48, 2.48, 2.58, 2.58	3.00	Average: 100%
	FH-04 Climbing cranes	1.74, 1.74, 1.90, 1.90	3.66, 3.82, 3.82, 3.98	2.48, 2.48, 2.58, 2.58	3.00	Average: 100%
	FH-05 Temporary ladder	1.56, 1.56, 1.72, 1.72	2.66, 2.66, 2.76, 2.76	3.14, 3.14, 3.24, 3.24	2.10	Average: 100%
	FH-06 Hole in the ground	2.76, 2.76, 2.92, 2.92	3.28, 3.28, 3.44, 3.44	3.32, 3.32, 3.42, 3.42	3.00	Average: 100%
	FH-07 Working on height unprotected	3.40, 3.40, 3.84, 3.84	4.06, 4.06, 4.32, 4.32	4.40, 4.40, 4.40, 4.40	4.27	High: 46%,Unacceptable: 54%
	FH-08 Through opening elevator shaft	3.24, 3.24, 3.40, 3.40	3.72, 3.72, 3.98, 3.98	3.34, 3.34, 3.44, 3.44	3.50	High 100%
Falling objects	FO-09 Part of climbing cranes, scaffolds	2.20, 2.20, 2.36, 2.36	3.48, 3.48, 3.74, 3.74	3.70, 3.70, 3.80, 3.80	3.00	Average: 100%
	FO-10 Operating, cleaning and clearing	2.30, 2.30, 2.30, 2.30	2.58, 2.58, 2.68, 2.68	3.12, 3.12, 3.22, 3.22	3.00	Average: 100%
	FO-11 Blown by wind	2.78, 2.78, 2.78, 2.78	3.02, 3.02, 3.28, 3.28	2.90, 2.90, 3.00, 3.00	3.00	Average: 100%
	FO-12 Hand-held tools	2.58, 2.58, 2.58, 2.58	3.04, 3.04, 3.30, 3.30	3.42, 3.42, 3.52, 3.52	3.00	Average: 100%
	FO-13 Hopper and bucket	2.50, 2.50, 2.66, 2.66	3.32, 3.32, 3.58, 3.58	2.96, 2.96, 3.06, 3.06	3.00	Average: 100%
	FO-14 Stacked items	2.40, 2.40, 2.40, 2.40	2.26, 2.26, 2.52, 2.52	3.12, 3.12, 3.22, 3.22	3.00	Average: 100%
	FO-15 Objects under pressure or tension	2.48, 2.64, 2.74, 2.90	3.16, 3.32, 3.42, 3.58	3.30, 3.30, 3.40, 3.40	3.00	Average: 100%
Manual handling	MH-16 Hoists	2.26, 2.26, 2.36, 2.36	3.00, 3.00, 3.00, 3.00	2.76, 2.76, 2.86, 2.86	3.00	Average: 100%
	MH-17 Mobile crane lifting	2.76, 2.92, 3.02, 3.18	3.66, 3.82, 3.92, 4.08	3.26, 3.26, 3.36, 3.36	3.37	Average: 26%, High: 74%
Equipment, machinery and tools	EQ-18 Heavy equipment	3.12, 3.12, 3.38, 3.38	3.66, 3.82, 3.92, 4.08	3.48, 3.48, 3.58, 3.58	3.50	High 100%
	EQ-19 Steel bar bending machine	2.40, 2.40, 2.66, 2.66	2.54, 2.54, 2.80, 2.80	3.38, 3.38, 3.48, 3.48	3.00	Average: 100%
	EQ-20 Vibrator machine	2.02, 2.02, 2.12, 2.12	2.54, 2.54, 2.80, 2.80	3.02, 3.02, 3.12, 3.12	3.00	Average: 100%
Electricity	EL-21 Wires	2.46, 2.46, 2.62, 2.62	3.66, 3.66, 3.92, 3.92	3.46, 3.46, 3.56, 3.56	3.00	Average: 100%
	EL-22 Electrical work	2.54, 2.54, 2.70, 2.70	4.22, 4.22, 4.48, 4.48	3.54, 3.54, 3.64, 3.64	3.63	High 100%
	EL-23 Overhead power lines	2.10, 2.10, 2.26, 2.26	3.66, 3.66, 3.92, 3.92	3.08, 3.08, 3.18, 3.18	3.00	Average: 100%
	EL-24 Arc welding machine	2.72, 2.72, 2.72, 2.72	3.38, 3.38, 3.64, 3.64	3.12, 3.12, 3.22, 3.22	3.00	Average: 100%
Slips and trips	ST-25 Tripping over building materials	2.04, 2.04, 2.14, 2.14	2.28, 2.28, 2.38, 2.38	3.60, 3.60, 3.70, 3.70	3.00	Average: 100%
	ST-26 Slipping on wet surfaces	2.24, 2.24, 2.34, 2.34	2.46, 2.46, 2.46, 2.46	3.40, 3.40, 3.50, 3.50	3.00	Average: 100%
	ST-27 Trips caused by small change	2.60, 2.60, 2.70, 2.70	2.74, 2.74, 2.84, 2.84	3.34, 3.34, 3.44, 3.44	3.00	Average: 100%
	ST-28 Trips caused by water pipes, rebar	2.60, 2.60, 2.70, 2.70	2.74, 2.74, 2.84, 2.84	2.86, 2.86, 3.16, 3.16	3.00	Average: 100%
	ST-29 Walking around construction site	2.12, 2.12, 2.12, 2.12	2.28, 2.28, 2.28, 2.28	3.14, 3.14, 3.44, 3.44	3.00	Average: 100%

Hazard Groups	Hazardous events	Probability of occurrence	Aggregated STFN Severity of consequence	Probability of consequence	Safety risk scores	Safety risk categories
Traffic hazards	TH-30 Collision with another vehicle	1.92, 1.92, 1.92, 1.92	3.00, 3.00, 3.00, 3.00	2.84, 2.84, 2.84, 2.84	2.76	Average: 100%
	TH-31 Collision with plant/people	1.92, 1.92, 1.92, 1.92	3.02, 3.02, 3.02, 3.02	3.02, 3.02, 3.02, 3.02	2.76	Average: 100%
Vehicle overturn	VO-32 Crane overturn	2.26, 2.26, 2.26, 2.26	3.20, 3.20, 3.20, 3.20	2.76, 2.76, 2.76, 2.76	3.00	Average: 100%
	VO-33 Mobile plant (Bobcats, tractor)	2.26, 2.26, 2.36, 2.36	3.84, 3.84, 3.84, 3.84	3.24, 3.24, 3.24, 3.24	3.00	Average: 100%
Fire and explosions	FE-34 Hot work	3.12, 3.12, 3.28, 3.28	3.78, 3.78, 4.04, 4.04	2.96, 2.96, 2.96, 2.96	3.10	Average: 80%, High: 20%
	FE-35 Working near flammables	3.08, 3.08, 3.24, 3.24	3.74, 3.90, 4.00, 4.16	2.76, 2.76, 2.76, 2.76	3.22	Average: 56%, High: 44%
	FE-36 Gas cylinder or hose leakage	3.08, 3.08, 3.24, 3.24	3.38, 3.54, 3.54, 3.70	3.26, 3.26, 3.26, 3.26	3.48	Average: 4%, High: 96%
	FE-37 Fire extinguisher has been discharged	2.70, 2.70, 2.86, 2.86	3.30, 3.46, 3.56, 3.72	3.58, 3.58, 3.58, 3.58	3.00	Average: 100%
Exposure to hazardous substances	ES-38 Solvents	2.48, 2.48, 2.58, 2.58	3.04, 3.04, 3.14, 3.14	2.94, 2.94, 2.94, 2.94	3.00	Average: 100%
	ES-39 Cement dust	2.56, 2.56, 2.74, 2.74	3.32, 3.32, 3.42, 3.42	3.50, 3.50, 3.50, 3.50	3.00	Average: 100%
	ES-40 Corrosive substances	2.02, 2.02, 2.02, 2.02	3.02, 3.02, 3.12, 3.12	3.04, 3.04, 3.04, 3.04	3.00	Average: 100%
Collapse of site structures	CO-41 Collapse of boom(cranes)	2.30, 2.30, 2.40, 2.40	3.66, 3.82, 3.82, 3.98	2.58, 2.58, 2.58, 2.58	3.00	Average: 100%
	CO-42 Collapse of scaffolding	2.12, 2.12, 2.38, 2.38	3.38, 3.54, 3.54, 3.70	2.94, 2.94, 2.94, 2.94	3.00	Average: 100%
	CO-43 Temporary structure	1.92, 1.92, 2.18, 2.18	3.38, 3.54, 3.64, 3.80	2.76, 2.76, 2.76, 2.76	2.79	Average: 100%
	CO-44 Steel sheet piles	2.08, 2.24, 2.34, 2.50	3.56, 3.72, 3.82, 3.98	3.14, 3.14, 3.14, 3.14	3.00	Average: 100%
	CO-45 Kingpost	2.08, 2.08, 2.34, 2.34	3.74, 3.90, 4.00, 4.16	3.14, 3.14, 3.14, 3.14	3.00	Average: 100%
Confined space	CS-46 Deep excavations	2.56, 2.72, 2.82,2.98	3.56, 3.72, 3.72, 3.88	3.14, 3.14, 3.14, 3.14	3.00	Average: 100%
	CS-47 Closed tanks	3.34, 3.34, 3.60, 3.60	3.30, 3.46, 3.46, 3.62	3.14, 3.14, 3.14, 3.14	3.28	Average: 44%, High: 56%
Ergonomic / Human factors	EH-48 Poor work posture	2.50, 2.50, 2.76, 2.76	2.92, 2.92, 3.18, 3.18	3.32, 3.32, 3.42, 3.42	3.00	Average: 100%
	EH-49 Repetitive movement	2.84, 2.84, 2.94, 2.94	2.80, 2.80, 2.90, 2.90	3.32, 3.32, 3.42, 3.42	3.00	Average: 100%
	EH-50 Extreme muscular exertion	2.66, 2.66, 2.76, 2.76	2.98, 3.14, 3.24, 3.40	3.42, 3.42, 3.52, 3.52	3.00	Average: 100%
Noise and vibration	NV-51 Piling	3.02, 3.02, 3.12, 3.12	3.00, 3.16, 3.36, 3.52	4.04, 4.04, 4.14, 4.14	3.26	Average: 48%, High: 52%
	NV-52 Excavation	2.38, 2.38, 2.64, 2.64	2.62, 2.78, 3.08, 3.24	3.76, 3.76, 3.86, 3.86	3.00	Average: 100%
	NV-53 Hammering	3.20, 3.36, 3.46, 3.62	2.90, 3.06, 3.36, 3.52	4.50, 4.50, 4.60, 4.60	3.67	High 100%
	NV-54 Vibrator machine	2.86, 2.86, 2.96, 2.96	3.00, 3.00, 3.30, 3.30	3.80, 3.80, 3.90, 3.90	3.00	Average: 100%
	NV-55 Hand-held power tools	1.74, 1.74, 1.84, 1.84	2.62, 2.62, 3.08, 3.08	3.40, 3.40, 3.50, 3.50	2.66	Average: 100%

Table 7-8: Safety risk magnitude when compared with two parameters (2Ps) in building construction project 1

Hazard groups	Hazardous event codes	Risk scores (2Ps)	Safety risk categories	Risk scores (3Ps)	Safety risk categories
Falls from height	FH-01	2.64	Average: 100%	2.61	Average: 100%
	FH-02	2.82	Average: 100%	2.72	Average: 100%
	FH-03	3.00	Average: 100%	3.00	Average: 100%
	FH-04	3.00	Average: 100%	3.00	Average: 100%
	FH-05	2.00	Average: 100%	2.10	Average: 100%
	FH-06	3.00	Average: 100%	3.00	Average: 100%
	FH-07	3.81	High: 100%	4.27	High: 46%,Unacceptable: 54%
	FH-08	3.00	Average: 100%	3.50	High 100%
Falling objects	FO-09	3.00	Average: 100%	3.00	Average: 100%
	FO-10	3.00	Average: 100%	3.00	Average: 100%
	FO-11	3.00	Average: 100%	3.00	Average: 100%
	FO-12	3.00	Average: 100%	3.00	Average: 100%
	FO-13	3.00	Average: 100%	3.00	Average: 100%
	FO-14	3.00	Average: 100%	3.00	Average: 100%
	FO-15	3.00	Average: 100%	3.00	Average: 100%
Manual handling	MH-16	3.00	Average: 100%	3.00	Average: 100%
	MH-17	3.11	Average: 78%, High: 22%	3.37	Average: 74%, High: 26%
Equipment, machinery and tools	EQ-18	3.14	Average: 90%, High: 10%	3.50	High 100%
	EQ-19	3.00	Average: 100%	3.00	Average: 100%
	EQ-20	3.00	Average: 100%	3.00	Average: 100%
Electricity	EL-21	3.00	Average: 100%	3.00	Average: 100%
	EL-22	3.63	High 100%	3.63	High 100%
	EL-23	3.00	Average: 100%	3.00	Average: 100%
	EL-24	3.00	Average: 100%	3.00	Average: 100%
Slips and trips	ST-25	3.00	Average: 100%	3.00	Average: 100%
	ST-26	3.00	Average: 100%	3.00	Average: 100%
	ST-27	3.00	Average: 100%	3.00	Average: 100%
	ST-28	3.00	Average: 100%	3.00	Average: 100%
	ST-29	3.00	Average: 100%	3.00	Average: 100%
Traffic hazards	TH-30	2.76	Average: 100%	2.76	Average: 100%
	TH-31	2.79	Average: 100%	2.76	Average: 100%
Vehicle overturn	VO-32	3.00	Average: 100%	3.00	Average: 100%
	VO-33	3.00	Average: 100%	3.00	Average: 100%
Fire and explosions	FE-34	3.10	Average: 80%, High: 20%	3.10	Average: 80%, High: 20%
	FE-35	3.22	Average: 56%, High: 44%	3.22	Average: 56%, High: 44%
	FE-36	3.00	Average: 100%	3.48	Average: 4%, High: 96%
	FE-37	3.00	Average: 100%	3.00	Average: 100%
Exposure to hazardous substances	ES-38	3.00	Average: 100%	3.00	Average: 100%
	ES-39	3.00	Average: 100%	3.00	Average: 100%
	ES-40	3.00	Average: 100%	3.00	Average: 100%
Collapse of site structures	CO-41	3.00	Average: 100%	3.00	Average: 100%
	CO-42	3.00	Average: 100%	3.00	Average: 100%
	CO-43	2.77	Average: 100%	2.79	Average: 100%
	CO-44	3.00	Average: 100%	3.00	Average: 100%
	CO-45	3.00	Average: 100%	3.00	Average: 100%
Confined space	CS-46	3.00	Average: 100%	3.00	Average: 100%
	CS-47	3.00	Average: 100%	3.28	Average: 44%, High: 56%

Table 7-8: (Continued)

Hazard groups	Hazardous event codes	Safety risk scores (2Ps)	Safety risk categories	Safety risk scores (3Ps)	Safety risk categories
Ergonomic / Human factors	EH-48	3.00	Average: 100%	3.00	Average: 100%
	EH-49	3.00	Average: 100%	3.00	Average: 100%
	EH-50	3.00	Average: 100%	3.00	Average: 100%
Noise and vibration	NV-51	3.20	Average: 60%, High: 40%	3.26	Average: 48%, High: 52%
	NV-52	3.00	Average: 100%	3.00	Average: 100%
	NV-53	3.67	High 100%	3.67	High 100%
	NV-54	3.00	Average: 100%	3.00	Average: 100%
	NV-55	2.35	Average: 100%	2.66	Average: 100%

Table 7-8 shows that when the third parameter, probability of consequence (PC), has been introduced in the proposed model, the safety risks scores from the two methods are slightly different. For example, for FH-02 (Placement ladder), FH-05 (Temporary ladder), FH-07 (Working on height unprotected), MH-17 (Mobile crane lifting), EQ-18 (Heavy equipment), FE-36 (Gas cylinder or hose leakage), CO-43 (Steel sheet piles), CS-47 (Closed tank), NV-51 (Piling), and NV-55 (Hand-held power tools), the hazardous event scores are higher than the results from the traditional method using two input parameters. After further analysis of the data, it was found that the results obtained from the proposed model have been affected by a higher probability of consequence (PC) and the severity of consequence to be estimated when the all hazardous events above can potentially become realities. Therefore, the obtained results revealed that using the developed construction safety risk assessment methodology improves the reliability and decreases ambiguity.

7.2.9 Calculation of the Criteria Weights

Once all the hazardous events of building construction project 1 have been identified and assessed based on the FRT, an MFAHP is applied to obtain the weighting factors of the hazardous groups. The process is described below.

An MFAHP based on trapezoidal fuzzy number is used to obtain the weights of the safety risk hazards to assess the overall safety risk magnitude of the construction project, especially when the pairwise comparison matrices become large datasets.

According to the basic principle of engineering judgement, experts were asked to make pairwise assessment of all the risks. It should be noted that *n* (*n*-1)/2, as mentioned earlier, and in this case, there are 14 × (14-1)/2 = 91 comparisons. However, according to Equations (5-6) and (5-7), using the MFAHP method, only *n*-1, there are (14-1) = 13 comparisons. Then, all aggregated pairwise comparison values were obtained, as shown in Table 7-9.

The aggregated STFN pairwise comparison can be obtained by Equation (6-3). For instance, the aggregated STFN pairwise comparison of FH vs. FO (*RH1,2*) is as follows:

$$\text{Aggregated STFN} = \frac{\text{STFN}_{1i} \times c_1 + \text{STFN}_{2i} \times c_2 \ldots + \text{STFN}_{ni} \times c_n}{1-\sum c_n}$$

$$\text{FH vs. FO}_{a} = \left\{\frac{3\times0.20+0.33\times0.18+2\times0.18+1\times0.18+2\times0.16+0.33\times0.10}{0.20+0.18+0.18+0.18+0.06+0.10}\right\} = 1.55$$

$$\text{FH vs. FO}_{b} = \left\{\frac{4\times0.20+0.33\times0.18+2\times0.18+1\times0.18+3\times0.16+0.33\times0.10}{0.20+0.18+0.18+0.18+0.06+0.10}\right\} = 1.91$$

$$\text{FH vs. FO}_{c} = \left\{\frac{4\times0.20+0.33\times0.18+2\times0.18+1\times0.18+3\times0.16+0.50\times0.10}{0.20+0.18+0.18+0.18+0.06+0.10}\right\} = 1.93$$

$$\text{FH vs. FO}_{d} = \left\{\frac{5\times0.20+0.33\times0.18+2\times0.18+1\times0.18+4\times0.16+0.50\times0.10}{0.20+0.18+0.18+0.18+0.06+0.10}\right\} = 2.29$$

FH vs. FO $\{a, b, c, d\} = \{1.55, 1.91, 1.93, 2.29\}$

Table 7-9: Experts' judgements of building construction project 1

Comparison	*Expert 1 (0.20)*		*Expert 2 (0.18)*		*Expert 3 (0.18)*		*Expert 4 (0.18)*		*Expert 5 (0.16)*		*Expert 6 (0.10)*		Aggregated STFN score
	Score	Converted STFN	Score	Converted STFN	Score	Converted STFN	Score	Converted STFN	Score	Converted STFN	Score	Converted STFN	
FH vs. FO (RH1, 2)	3.00, 4.00, 5.00	3.00, 4.00, 4.00, 5.00	0.33	0.33, 0.33, 0.33, 0.33	2.00	2.00, 2.00, 2.00, 2.00	1.00	1.00, 1.00, 1.00, 1.00	2.00, 3.00, 4.00	2.00, 3.00, 3.00, 4.00	0.33, 0.50	0.33, 0.33, 0.50, 0.50	1.55, 1.91, 1.93, 2.29
FO vs. MH (RH2, 3)	1.00	1.00, 1.00, 1.00, 1.00	2.00	2.00, 2.00, 2.00, 2.00	1.00	1.00, 1.00, 1.00, 1.00	1.00	1.00, 1.00, 1.00, 1.00	0.14, 0.17, 0.20	0.14, 0.17, 0.17, 0.20	1.00, 2.00	1.00, 1.00, 2.00, 2.00	1.04, 1.05, 1.15, 1.15
MH vs. EQ (RH3, 4)	3.00, 4.00, 5.00	3.00, 4.00, 4.00 5.00	4.00	4.00, 4.00, 4.00, 4.00	0.20	0.20, 0.20, 0.20, 0.20	1.00	1.00, 1.00, 1.00, 1.00	0.11, 0.13, 0.14	0.11, 0.13, 0.13, 0.14	4.00, 5.00	4.00, 4.00, 5.00, 5.00	1.95, 2.16, 2.26, 2.46
EQ vs. EL (RH4, 5)	1.00	1.00, 1.00, 1.00, 1.00	2.00	2.00, 2.00, 2.00, 2.00	3.00	3.00, 3.00, 3.00, 3.00	0.20	0.20, 0.20, 0.20, 0.20	7.00, 8.00, 9.00	7.00, 8.00, 8.00, 9.00	1.00, 2.00	1.00, 1.00, 2.00, 2.00	2.36, 2.52, 2.62, 2.78
EL vs. ST (RH5, 6)	3.00, 4.00, 5.00	3.00, 4.00, 4.00 5.00	1.00	1.00, 1.00, 1.00, 1.00	0.25	0.25, 0.25, 0.25, 0.25	9.00	9.00, 9.00, 9.00, 9.00	7.00, 8.00, 9.00	7.00, 8.00, 8.00, 9.00	0.50, 1.00	0.50, 0.50, 1.00, 1.00	3.62, 3.98, 4.03, 4.39
ST vs. TH (RH6, 7)	4.00, 5.00	4.00, 4.00, 5.00, 5.00	0.50	0.50, 0.50, 0.50, 0.50	0.33	0.33, 0.33, 0.33, 0.33	0.11	0.11, 0.11, 0.11, 0.11	4.00, 5.00, 6.00	4.00, 5.00, 5.00, 6.00	0.11, 0.13, 0.14	0.11, 0.13, 0.13 0.14	1.62, 1.78, 1.98, 2.14
TH vs. VO (RH7, 8)	0.20, 0.25,	3.00, 4.00,	2.00	2.00, 2.00	0.33	0.33, 0.33	0.11	0.11, 0.11	1.00	1.00, 1.00	2.00	2.00, 2.00	0.84, 0.85

Table 7-9: Experts' judgements of building construction project 1(Cont.)

Comparison	*Expert 1 (0.20)*		*Expert 2 (0.18)*		*Expert 3 (0.18)*		*Expert 4 (0.18)*		*Expert 5 (0.16)*		*Expert 6 (0.10)*		Aggregated STFN score
	Score	Converted STFN	Score	Converted STFN	Score	Converted STFN	Score	Convert STFN	Score	Converted STFN	Score	Converted STFN	
	0.33	3.00, 4.00,		2.00		0.33, 0.33		0.11, 0.11		1.00, 1.00		2.00, 2.00	0.85, 0.87
VO vs. FE (RH8, 9)	3.00, 4.00, 5.00	3.00, 4.00, 4.00, 5.00	0.33	0.33, 0.33, 0.33, 0.33	0.33	0.33, 0.33, 0.33, 0.33	0.11	0.11, 0.11, 0.11, 0.11	0.14, 0.17, 0.20	0.14, 0.17, 0.17, 0.20	0.11, 0.13, 0.14	0.11, 0.13, 0.13, 0.14	0.77, 0.98, 0.98, 1.18
EF vs. ES (RH9, 10)	3.00, 4.00, 5.00	3.00, 4.00, 4.00, 5.00	3.00	3.00, 3.00, 3.00, 3.00	3.00	3.00, 3.00, 3.00, 3.00	9.00	9.00, 9.00, 9.00, 9.00	2.00, 3.00	2.00, 2.00, 3,00, 3.00	3.00, 4.00	3.00, 3.00, 4.00, 4.00	3.92, 4.12, 4.38, 4.58
ES vs. CO (RH10, 11)	0.14, 0.17, 0.20	0.14, 0.17, 0.17, 0.20	4.00	4.00, 4.00, 4.00, 4.00	2.00	2.00, 2.00, 2.00, 2.00	0.11	0.11, 0.11, 0.11, 0.11	0.11, 0.13, 0.14	0.11, 0.13, 0.13, 0.14	3.00, 4.00	3.00, 3.00, 4.00, 4.00	1.45, 1.45, 1.55, 1.56
CO vs. CS (RH11, 12)	1.00	1.00, 1.00, 1.00, 1.00	0.33	0.33, 0.33, 0.33, 0.33	0.14	0.14, 0.14, 0.14, 0.14	9.00	9.00, 9.00, 9.00, 9.00	7.00, 8.00, 9.00	7.00, 8.00, 8.00, 9.00	0.33, 0.50	0.33, 0.33, 0.50, 0.50	3.06, 3.22, 3.23, 3.39
CS vs. EH (RH12, 13)	7.00	7.00, 7.00, 7.00, 7.00	3.00	3.00, 3.00, 3.00, 3.00	3.00	3.00, 3.00, 3.00, 3.00	0.11	0.11, 0.11, 0.11, 0.11	7.00, 8.00, 9.00	7.00, 8.00, 8.00, 9.00	3.00, 4.00	3.00, 3.00, 4.00, 4.00	3.92, 4.08, 4,18, 4.34
EH vs. NV (RH13, 14)	1.00	1.00, 1.00, 1.00, 1.00	2.00	2.00, 2.00, 2.00, 2.00	0.25	0.25, 0.25, 0.25, 0.25	9.00	9.00, 9.00, 9.00, 9.00	0.14, 0.13, 0.11	0.14, 0.13, 0.13, 0.11	1.00, 2.00	1.00, 1.00, 2.00, 2.00	2.35, 2.35, 2.45, 2.44

Once the all the aggregated pairwise comparison values have been calculated, the pairwise comparison matrix of all the safety risks can be established by Equations (5-1) and (5-3) on based on the completed trapezoidal fuzzy number preference relation decision matrix as shown in Table 7-10.

$$\text{The pairwise comparison matrix } (P1) = (X_{ij}) = \begin{array}{c} \\ R_1 \\ R_2 \\ \vdots \\ R_{14} \end{array} \begin{array}{c} \begin{array}{cccc} R_1 & R_2 & \cdots & R_{14} \end{array} \\ \begin{bmatrix} 1,1,1,1 & x_{1,2} & \cdots & x_{1,14} \\ x_{21} & 1,1,1,1 & \cdots & x_{2,14} \\ \vdots & \vdots & \ddots & \vdots \\ x_{14,1} & x_{14,2} & \cdots & 1,1,1,1 \end{bmatrix} \end{array}$$

It should be noted that $FH_{1,6}$ and $FH_{1,14}$ are not in the interval [1/9-9]. The completed trapezoidal fuzzy number preference relation decision matrix is needed to transfer the MFAHP preference relation decision matrix in the interval. In this case, by using Equation (5-8) the maximum of $P1 = max\ (x_{ij})$ = FH $x_{1,14}$ = 4.5E+04, and the following transformation functions are applied as

$$f(x_a) = x_a^{1/\log_9 4.5E+04},\ f(x_b) = x_b^{1/\log_9 4.5E+04},$$

$$f(x_c) = x_c^{1/\log_9 4.5E+04},\ f(x_d) = x_d^{1/\log_9 4.5E+04}$$

Table 7-11 lists the transferred entries that are employed as the MFAHP preference relation decision matrix for the modified fuzzy-AHP processes.

Table 7-10: Completed trapezoidal fuzzy number preference relation decision matrix preference matrix for building construction project 1

	FH	FO	MH	EQ	EL	ST	TH	VO	FE	ES	CO	EH	CS	NV
FH	1.00, 1.00, 1.00, 1.00	1.55, 1.91, 1.93, 2.29	1.62, 2.00, 2.21, 2.64	3.16, 4.32, 5.00, 6.48	7.45, 10.87, 13.07, 18.00	26.93, 43.20, 52.60, 7.9E+01	43.62, 7.7E+01, 1.0E+02, 1.7E+02	3.7E+01, 6.5E+01, 8.9E+01, 1.5E+02	2.8E+01, 6.4E+01, 8.7E+01, 1.7E+02	1.1E+02, 2.6E+02, 3.8E+02, 7.9E+02	1.6E+02, 3.8E+02, 5.9E+02, 1.2E+03	4.9E+02, 1.2E+03, 1.9E+03, 4.2E+03	1.9E+03, 5.0E+03, 7.9E+03, 1.8E+04	4.5E+03, 1.2E+04, 1.9E+04, 4.5E+04
FO	0.44, 0.52, 0.52, 0.64	1.00, 1.00, 1.00, 1.00	1.04, 1.05, 1.15, 1.15	2.04, 2.26, 2.59, 2.83	4.80, 5.68, 6.77, 7.86	17.34, 22.59, 27.26, 34.47	28.10, 4.0E+01, 5.4E+01, 7.4E+01	2.4E+01, 3.4E+01, 4.6E+01, 6.4E+01	1.8E+01, 3.3E+01, 4.5E+01, 7.6E+01	7.1E+01, 1.4E+02, 2.0E+02, 3.5E+02	1.0E+02, 2.0E+02, 3.0E+02, 5.4E+02	3.2E+02, 6.4E+02, 9.8E+02, 1.8E+03	1.2E+03, 2.6E+03, 4.1E+03, 7.9E+03	2.9E+03, 6.1E+03, 1.0E+04, 1.9E+04
MH	0.38, 0.45, 0.50, 0.62	0.87, 0.87, 0.95, 0.96	1.00, 1.00, 1.00, 1.00	1.95, 2.16, 2.26, 2.46	4.60, 5.43, 5.90, 6.82	16.64, 21.57, 23.76, 29.93	26.96, 3.8E+01, 4.7E+01, 6.4E+01	2.3E+01, 3.3E+01, 4.0E+01, 5.5E+01	1.7E+01, 3.2E+01, 3.9E+01, 6.6E+01	6.8E+01, 1.3E+02, 1.7E+02, 3.0E+02	9.9E+01, 1.9E+02, 2.6E+02, 4.7E+02	3.0E+02, 6.2E+02, 8.6E+02, 1.6E+03	1.1E+03, 2.5E+03, 3.6E+03, 6.9E+03	2.7E+03, 5.8E+03, 8.8E+03, 1.6E+04
EQ	0.15, 0.20, 0.23, 0.32	0.35, 0.39, 0.44, 0.49	0.41, 0.44, 0.46, 0.51	1.00, 1.00, 1.00, 1.00	2.36, 2.52, 2.62, 2.78	8.52, 10.00, 10.53, 12.17	13.80, 17.82, 20.87, 26.09	1.2E+01, 1.5E+01, 1.8E+01, 2.3E+01	8.9E+00, 1.5E+01, 1.7E+01, 2.7E+01	3.5E+01, 6.1E+01, 7.6E+01, 1.2E+02	5.0E+01, 8.8E+01, 1.2E+02, 1.9E+02	1.5E+02, 2.8E+02, 3.8E+02, 6.5E+02	6.0E+02, 1.1E+03, 1.6E+03, 2.8E+03	1.4E+03, 2.7E+03, 3.9E+03, 6.8E+03
EL	5.6E-02, 0.08, 0.09, 0.13	0.13, 0.15, 0.18, 0.21	0.15, 0.17, 0.18, 0.22	0.36, 0.38, 0.40, 0.42	1.00, 1.00, 1.00, 1.00	3.62, 3.98, 4.03, 4.39	5.86, 7.08, 7.98, 9.40	4.92, 6.02, 6.78, 8.13	3.8E+00, 5.9E+00, 6.6E+00, 9.6E+00	1.5E+01, 2.4E+01, 2.9E+01, 4.4E+01	2.1E+01, 3.5E+01, 4.5E+01, 6.9E+01	6.5E+01, 1.1E+02, 1.5E+02, 2.3E+02	2.5E+02, 4.6E+02, 6.1E+02, 1.0E+03	6.0E+02, 1.0E+03, 1.5E+03, 2.5E+03
ST	1.3E-02, 1.9E-02, 2.3E-02, 3.7E-02	2.9E-02, 0.04, 0.04, 0.06	0.03, 0.04, 0.05, 0.06	0.08, 0.09, 0.10, 0.12	0.23, 0.25, 0.25, 0.28	1.00, 1.00, 1.00, 1.00	1.62, 1.78, 1.98, 2.14	1.36, 1.51, 1.68, 1.85	1.05, 1.48, 1.65, 2.20	4.11, 6.1E+00, 7.2E+00, 1.0E+01	5.9E+00, 8.8E+00, 1.1E+01, 1.6E+01	1.8E+01, 2.8E+01, 3.6E+01, 5.3E+01	7.1E+01, 1.1E+02, 1.5E+02, 2.3E+02	1.6E+02, 2.7E+02, 3.7E+02, 5.6E+02
TH	5.9E-03, 9.6E-03, 1.3E-02, 2.3E-02	1.4E-02, 1.9E-02, 2.5E-02, 3.6E-02	1.6E-02, 2.1E-02, 2.6E-02, 3.7E-02	3.8E-02, 4.8E-02, 5.6E-02, 7.2E-02	1.1E-01, 1.3E-01, 1.4E-01, 1.7E-01	0.47, 0.50, 0.56, 0.62	1.00, 1.00, 1.00, 1.00	0.84, 0.85, 0.85, 0.87	0.65, 0.83, 0.83, 1.02	2.54, 3.42, 3.64, 4.69	3.7E+00, 4.9E+00, 5.6E+00, 7.3E+00	1.1E+01, 1.6E+01, 1.8E+01, 2.5E+01	4.4E+01, 6.5E+01, 7.6E+01, 1.0E+02	1.0E+02, 1.5E+02, 1.8E+02, 2.6E+02

	FH	FO	MH	EQ	EL	ST	TH	VO	FE	ES	CO	EH	CS	NV
VO	6.8E-03, 1.1E-02, 1.5E-02, 2.7E-02	1.6E-02, 2.2E-02, 2.9E-02, 4.2E-02	1.8E-02, 2.5E-02, 3.1E-02, 4.4E-02	4.4E-02, 5.6E-02, 6.6E-02, 8.6E-02	1.2E-01, 1.5E-01, 1.7E-01, 2.0E-01	5.4E-01, 5.9E-01, 6.6E-01, 7.4E-01	0.16, 0.18, 0.18, 0.19	1.00, 1.00, 1.00, 1.00	0.77, 0.98, 0.98, 1.18	3.03, 4.03, 4.29, 5.43	4.37, 5.86, 6.66, 8.48	1.3E+01, 1.9E+01, 2.2E+01, 2.9E+01	5.2E+01, 7.7E+01, 9.0E+01, 1.2E+02	1.2E+02, 1.8E+02, 2.2E+02, 3.0E+02
FE	5.8E-03, 1.2E-02, 1.6E-02, 3.5E-02	1.3E-02, 2.2E-02, 3.0E-02, 5.5E-02	1.5E-02, 2.6E-02, 3.1E-02, 5.7E-02	3.7E-02, 5.8E-02, 6.7E-02, 1.1E-01	1.0E-01, 1.5E-01, 1.7E-01, 2.6E-01	4.6E-01, 6.1E-01, 6.8E-01, 9.5E-01	0.98, 1.20, 1.20, 1.54	0.84, 1.02, 1.02, 1.30	1.00, 1.00, 1.00, 1.00	3.92, 4.12, 4.38, 4.58	5.67, 5.99, 6.81, 7.15	1.7E+01, 1.9E+01, 2.2E+01, 2.4E+01	6.7E+01, 7.8E+01, 9.2E+01, 1.0E+02	1.6E+02, 1.8E+02, 2.2E+02, 2.5E+02
ES	1.3E-03, 2.6E-03, 3.8E-03, 9.0E-03	2.9E-03, 5.1E-03, 7.3E-03, 1.4E-02	3.3E-03, 5.8E-03, 7.6E-03, 1.5E-02	8.2E-03, 1.3E-02, 1.6E-02, 2.9E-02	2.3E-02, 3.4E-02, 4.1E-02, 6.7E-02	9.9E-02, 1.4E-01, 1.6E-01, 2.4E-01	2.1E-01, 2.7E-01, 2.9E-01, 3.9E-01	0.18, 0.23, 0.25, 0.33	0.22, 0.23, 0.24, 0.26	1.00, 1.00, 1.00, 1.00	1.45, 1.45, 1.55, 1.56	4.42, 4.68, 5.03, 5.30	17.32, 19.09, 21.01, 23.01	4.1E+01, 4.5E+01, 5.1E+01, 5.6E+01
CO	8.1E-04, 1.7E-03, 2.6E-03, 6.2E-03	1.8E-03, 3.3E-03, 5.0E-03, 9.7E-03	2.1E-03, 3.8E-03, 5.2E-03, 1.0E-02	5.2E-03, 8.5E-03, 1.1E-02, 2.0E-02	1.5E-02, 2.2E-02, 2.8E-02, 4.7E-02	6.4E-02, 8.9E-02, 1.1E-01, 1.7E-01	1.4E-01, 1.8E-01, 2.0E-01, 2.7E-01	1.2E-01, 1.5E-01, 1.7E-01, 2.3E-01	1.4E-01, 1.5E-01, 1.7E-01, 1.8E-01	0.64, 0.64, 0.69, 0.69	1.00, 1.00, 1.00, 1.00	3.06, 3.22, 3.23, 3.39	11.99, 13.13, 13.52, 14.73	28.13, 30.79, 33.07, 35.98
EH	2.4E-04, 5.2E-04, 8.1E-04, 2.0E-03	5.4E-04, 1.0E-03, 1.6E-03, 3.2E-03	6.3E-04, 1.2E-03, 1.6E-03, 3.3E-03	1.5E-03, 2.6E-03, 3.5E-03, 6.5E-03	4.3E-03, 6.8E-03, 8.8E-03, 1.5E-02	1.9E-02, 2.8E-02, 3.5E-02, 5.5E-02	4.0E-02, 5.5E-02, 6.2E-02, 8.9E-02	3.5E-02, 4.6E-02, 5.3E-02, 7.5E-02	4.1E-02, 4.5E-02, 5.2E-02, 5.8E-02	1.9E-01, 2.0E-01, 2.1E-01, 2.3E-01	0.29, 0.31, 0.31, 0.33	1.00, 1.00, 1.00, 1.00	3.92, 4.08, 4.18, 4.34	9.20, 9.57, 10.22, 10.60
CS	5.5E-05, 1.3E-04, 2.0E-04, 5.2E-04	1.3E-04, 2.4E-04, 3.8E-04, 8.1E-04	1.4E-04, 2.8E-04, 4.0E-04, 8.4E-04	3.5E-04, 6.3E-04, 8.6E-04, 1.6E-03	9.8E-04, 1.6E-03, 2.2E-03, 3.9E-03	4.3E-03, 6.6E-03, 8.6E-03, 1.4E-02	9.3E-03, 1.3E-02, 1.5E-02, 2.3E-02	8.0E-03, 1.1E-02, 1.3E-02, 1.9E-02	9.5E-03, 1.1E-02, 1.3E-02, 1.5E-02	4.3E-02, 4.8E-02, 5.2E-02, 5.8E-02	6.8E-02, 7.4E-02, 7.6E-02, 0.08	0.23, 0.24, 0.25, 0.26	1.00, 1.00, 1.00, 1.00	2.35, 2.35, 2.45, 2.44
NV	2.2E-05, 5.1E-05, 8.5E-05, 2.2E-04	5.1E-05, 9.9E-05, 1.6E-04, 3.4E-04	5.9E-05, 1.1E-04, 1.7E-04, 3.6E-04	1.5E-04, 2.6E-04, 3.7E-04, 7.0E-04	4.0E-04, 6.7E-04, 9.2E-04, 1.7E-03	1.8E-03, 2.7E-03, 3.7E-03, 6.0E-03	3.8E-03, 5.3E-03, 6.5E-03, 9.7E-03	3.3E-03, 4.5E-03, 5.5E-03, 8.1E-03	3.9E-03, 4.4E-03, 5.4E-03, 6.3E-03	1.8E-02, 1.9E-02, 2.2E-02, 5.8E-02	2.8E-02, 3.0E-02, 0.03, 0.04	0.09, 0.10, 0.10, 0.11	0.41, 0.41, 0.43, 0.43	1.00, 1.00, 1.00, 1.00

Table 7-11: MFAHP preference relation decision matrix for building construction project 1

	FH	FO	MH	EQ	EL	ST	TH	VO	FE	ES	CO	EH	CS	NV
FH	1.00, 1.00, 1.00, 1.00	1.09, 1.14, 1.14, 1.19	1.10, 1.15, 1.18, 1.22	1.27, 1.35, 1.39, 1.47	1.51, 1.63, 1.69, 1.81	1.97, 2.17, 2.26, 2.45	2.17, 2.44, 2.60, 2.87	2.09, 2.36, 2.51, 2.78	1.99, 2.35, 2.50, 2.88	2.63, 3.14, 3.38, 3.94	2.83, 3.39, 3.70, 4.31	3.56, 4.31, 4.71, 5.54	4.72, 5.75, 6.32, 7.49	5.62, 6.85, 7.59, 9.00
FO	0.84, 0.87, 0.88, 0.91	1.00, 1.00, 1.00, 1.00	1.01, 1.01, 1.03, 1.03	1.16, 1.18, 1.22, 1.24	1.38, 1.43, 1.48, 1.53	1.80, 1.90, 1.97, 2.07	1.98, 2.13, 2.27, 2.42	1.91, 2.06, 2.19, 2.35	1.81, 2.06, 2.18, 2.43	2.40, 2.75, 2.96, 3.32	2.59, 2.97, 3.24, 3.64	3.26, 3.77, 4.12, 4.68	4.31, 5.03, 5.52, 6.32	5.14, 6.00, 6.64, 7.59
MH	0.82, 0.85, 0.87, 0.91	0.97, 0.97, 0.99, 0.99	1.00, 1.00, 1.00, 1.00	1.15, 1.17, 1.18, 1.20	1.37, 1.41, 1.44, 1.48	1.78, 1.88, 1.92, 2.01	1.97, 2.11, 2.20, 2.35	1.90, 2.04, 2.13, 2.28	1.80, 2.04, 2.12, 2.36	2.38, 2.72, 2.87, 3.23	2.57, 2.94, 3.15, 3.54	3.23, 3.74, 4.00, 4.54	4.27, 4.99, 5.37, 6.14	5.09, 5.94, 6.45, 7.38
EQ	0.68, 0.72, 0.74, 0.79	0.81, 0.82, 0.85, 0.86	0.83, 0.85, 0.85, 0.87	1.00, 1.00, 1.00, 1.00	1.19, 1.21, 1.22, 1.23	1.55, 1.60, 1.62, 1.67	1.71, 1.81, 1.87, 1.95	1.65, 1.75, 1.80, 1.90	1.57, 1.74, 1.80, 1.96	2.07, 2.33, 2.43, 2.68	2.24, 2.51, 2.66, 2.94	2.81, 3.19, 3.39, 3.78	3.73, 4.26, 4.54, 5.11	4.44, 5.07, 5.46, 6.13
EL	0.55, 0.59, 0.61, 0.66	0.65, 0.68, 0.70, 0.72	0.67, 0.96, 0.71, 0.73	0.81, 0.82, 0.83, 0.84	1.00, 1.00, 1.00, 1.00	1.30, 1.33, 1.33, 1.35	1.44, 1.49, 1.53, 1.58	1.39, 1.45, 1.48, 1.54	1.31, 1.44, 1.47, 1.59	1.74, 1.92, 2.00, 2.18	1.88, 2.08, 2.19, 2.38	2.36, 2.64, 2.78, 3.06	3.12, 3.52, 3.73, 4.14	3.72, 4.20, 4.48, 4.97
ST	0.41, 0.44, 0.46, 0.51	0.48, 0.51, 0.53, 0.56	0.50, 0.52, 0.53, 0.56	0.60, 0.62, 0.62, 0.64	0.74, 0.75, 0.75, 0.77	1.00, 1.00, 1.00, 1.00	1.10, 1.13, 1.15, 1.17	1.07, 1.09, 1.11, 1.14	1.01, 1.08, 1.11, 1.18	1.34, 1.45, 1.50, 1.61	1.44, 1.57, 1.64, 1.76	1.81, 1.99, 2.09, 2.26	2.40, 2.65, 2.80, 3.06	2.86, 3.16, 3.37, 3.67
TH	0.35, 0.39, 0.41, 0.46	0.41, 0.44, 0.47, 0.50	0.43, 0.45, 0.47, 0.51	0.51, 0.54, 0.55, 0.58	0.63, 0.65, 0.67, 0.70	0.86, 0.87, 0.89, 0.91	1.00, 1.00, 1.00, 1.00	0.96, 0.97, 0.97, 0.97	0.91, 0.96, 0.96, 1.01	1.21, 1.29, 1.30, 1.37	1.31, 1.39, 1.43, 1.51	1.64, 1.77, 1.82, 1.93	2.17, 2.36, 2.44, 2.61	2.59, 2.81, 2.93, 3.1

	FH	FO	MH	EQ	EL	ST	TH	VO	FE	ES	CO	EH	CS	NV
VO	0.36, 0.40, 0.42, 0.48	0.43, 0.46, 0.48, 0.52	0.44, 0.47, 0.49, 0.53	0.53, 0.55, 0.57, 0.60	0.65, 0.68, 0.69, 0.72	0.88, 0.90, 0.92, 0.94	1.03, 1.03, 1.03, 1.04	1.00, 1.00, 1.00, 1.00	0.95, 1.00, 1.00, 1.04	1.26, 1.33, 1.35, 1.41	1.35, 1.44, 1.48, 1.55	1.70, 1.83, 1.88, 1.99	2.25, 2.44, 2.52, 2.69	2.69, 2.90, 3.03, 3.23
FE	0.35, 0.40, 0.43, 0.50	0.41, 0.46, 0.49, 0.55	0.42, 0.47, 0.49, 0.56	0.51, 0.56, 0.58, 0.64	0.63, 0.68, 0.69, 0.76	0.85, 0.90, 0.92, 0.99	0.99, 1.04, 1.04, 1.09	0.97, 1.00, 1.00, 1.05	1.00, 1.00, 1.00, 1.00	1.32, 1.34, 1.35, 1.37	1.43, 1.44, 1.48, 1.50	1.80, 1.84, 1.89, 1.92	2.38, 2.45, 2.53, 2.60	2.83, 2.92, 3.04, 3.12
ES	0.25, 0.30, 0.32, 0.38	0.30, 0.34, 0.36, 0.42	0.31, 0.35, 0.37, 0.42	0.37, 0.41, 0.43, 0.48	0.46, 0.50, 0.52, 0.57	0.62, 0.67, 0.69, 0.75	0.73, 0.77, 0.78, 0.83	0.71, 0.74, 0.75, 0.80	0.73, 0.74, 0.75, 0.76	1.00, 1.00, 1.00, 1.00	1.08, 1.08, 1.09, 1.10	1.36, 1.37, 1.39, 1.41	1.80, 1.83, 1.87, 1.90	2.14, 2.18, 2.24, 2.29
CO	0.23, 0.27, 0.29, 0.35	0.27, 0.31, 0.34, 0.39	0.28, 0.32, 0.34, 0.39	0.34, 0.38, 0.40, 0.45	0.42, 0.46, 0.48, 0.53	0.57, 0.61, 0.64, 0.69	0.66, 0.70, 0.72, 0.77	0.64, 0.68, 0.70, 0.74	0.67, 0.67, 0.69, 0.70	0.91, 0.91, 0.93, 0.93	1.00, 1.00, 1.00, 1.00	1.26, 1.27, 1.27, 1.29	1.66, 1.70, 1.71, 1.74	1.98, 2.02, 2.05, 2.09
EH	0.18, 0.21, 0.23, 0.28	0.21, 0.24, 0.27, 0.31	0.22, 0.25, 0.27, 0.31	0.26, 0.30, 0.31, 0.36	0.33, 0.36, 0.38, 0.42	0.44, 0.48, 0.50, 0.55	0.52, 0.55, 0.57, 0.61	0.50, 0.53, 0.55, 0.59	0.52, 0.53, 0.54, 0.56	0.71, 0.72, 0.73, 0.74	0.78, 0.79, 0.79, 0.80	1.00, 1.00, 1.00, 1.00	1.32, 1.33, 1.34, 1.35	1.58, 1.59, 1.61, 1.62
CS	0.13, 0.16, 0.17, 0.21	0.16, 0.18, 0.20, 0.23	0.16, 0.19, 0.20, 0.23	0.20, 0.22, 0.23, 0.27	0.24, 0.27, 0.28, 0.32	0.33, 0.36, 0.38, 0.42	0.38, 0.41, 0.42, 0.46	0.37, 0.40, 0.41, 0.44	0.38, 0.40, 0.41, 0.42	0.53, 0.54, 0.55, 0.56	0.58, 0.59, 0.59, 0.60	0.74, 0.75, 0.75, 0.76	1.00, 1.00, 1.00, 1.00	1.19, 1.19, 1.20, 1.20
NV	0.11, 0.13, 0.15, 0.18	0.13, 0.15, 0.17, 0.19	0.14, 0.16, 0.17, 0.20	0.16, 0.18, 0.20, 0.23	0.20, 0.22, 0.24, 0.27	0.27, 0.30, 0.32, 0.35	0.32, 0.34, 0.36, 0.39	0.31, 0.33, 0.34, 0.37	0.32, 0.33, 0.34, 035	0.44, 0.45, 0.46, 0.46	0.48, 0.49, 0.49, 0.50	0.62, 0.62, 0.63, 0.63	0.83, 0.83, 0.84, 0.84	1.00, 1.00, 1.00, 1.00

Using Equations (5-9) and (5-10), the geometric mean method and the weights of all the hazard groups are obtained as follows:

$$X_{FH} = \{a_1, b_1, c_1, d_1\} = \begin{Bmatrix} \sqrt[14]{\prod_{j=1}^{14} a_{1j}}, \\ \sqrt[14]{\prod_{j=1}^{14} b_{1j}}, \\ \sqrt[14]{\prod_{j=1}^{14} c_{1j}}, \\ \sqrt[14]{\prod_{j=1}^{14} d_{1j}} \end{Bmatrix} = \begin{Bmatrix} \sqrt[14]{1 \times 1.09 \times 1.10 \times 1.27 \times \ldots \times 5.62}, \\ \sqrt[14]{1 \times 1.14 \times 1.15 \times 1.35 \times \ldots \times 6.85}, \\ \sqrt[14]{1 \times 1.14 \times 1.18 \times 1.39 \times \ldots \times 7.59}, \\ \sqrt[14]{1 \times 1.19 \times 1.12 \times 1.47 \times \ldots \times 9.00} \end{Bmatrix}$$

$$X_{FH} = \{2.082, 2.346, 2.476, 2.744\}$$

Similarity, X_{FO}, X_{MH}, X_{EQ}, X_{EL}, X_{ST}, X_{TH}, X_{FE}, X_{ES}, X_{CO}, X_{EH}, X_{CS} and X_{NV} can be calculated:

$X_{FO} = \{1.892, 2.054, 2.166, 2.328\}$ $X_{MH} = \{1.870, 2.029, 2.112, 2.268\}$

$X_{EQ} = \{1.614, 1.729, 1.790, 1.905\}$ $X_{EL} = \{1.341, 1.428, 1.473, 1.560\}$

$X_{ST} = \{1.015, 1.075, 1.108, 1.168\}$ $X_{TH} = \{0.897, 0.946, 0.972, 1.024\}$

$X_{VO} = \{0.927, 0.978, 1.005, 1.058\}$ $X_{FE} = \{0.930, 0.982, 1.009, 1.075\}$

$X_{ES} = \{0.688, 0.729, 0.751, 0.803\}$ $X_{CO} = \{0.631, 0.668, 0.693, 0.741\}$

$X_{EH} = \{0.493, 0.525, 0.545, 0.586\}$ $X_{CS} = \{0.366, 0.392, 0.408, 0.442\}$

$X_{NV} = \{0.305, 0.326, 0.343, 0.375\}$

The fuzzy weight factors can be calculated by

$$W_{FH} = \{a_1, b_1, c_1, d_1\} = \left\{\begin{matrix} \frac{a_1}{\sum_{j=1}^{14} d_j}, \\ \frac{b_1}{\sum_{j=1}^{14} dc_j}, \\ \frac{c_1}{\sum_{j=1}^{14} b_j}, \\ \frac{d_1}{\sum_{j=1}^{14} a_j} \end{matrix}\right\} = \left\{\begin{matrix} \frac{2.082}{\{2.082+1.892+1.870+\cdots+0.305\}}, \\ \frac{2.346}{\{2.346+2.054+2.029+\cdots+0.326\}}, \\ \frac{2.476}{\{2.476+2.166+2.116+\cdots+0.343\}}, \\ \frac{2.744}{\{2.744+2.328+2.268+\cdots+0.375\}} \end{matrix}\right\}$$

W_{FH} = {0.14, 0.14, 0.15, 0.15} W_{FO} = {0.13, 0.13, 0.13, 0.13}

W_{MH} = {0.12, 0.13, 0.13, 0.13} W_{EQ} = {0.11, 0.11, 0.11, 0.11}

W_{EL} = {0.09, 0.09, 0.09, 0.09} W_{ST} = {0.07, 0.07, 0.07, 0.06}

W_{TH} = {0.06, 0.06, 0.06, 0.06} W_{VO} = {0.06, 0.06, 0.06, 0.06}

W_{FE} = {0.06, 0.06, 0.06, 0.06} W_{ES} = {0.05, 0.04, 0.04, 0.04}

W_{CO}= {0.04, 0.04, 0.04, 0.04} W_{EH} = {0.03, 0.03, 0.03, 0.03}

W_{CS} = {0.02, 0.02, 0.02, 0.02} W_{NV} = {0.02, 0.02, 0.02, 0.02}

By using Equation (5-11), defuzzification is applied to convert to crisp numbers:

$$W_{FH} = \left\{\frac{a_{FH}+2(b_{FH}+c_{FH})+d_{FH}}{6}\right\} = \left\{\frac{0.14+2(0.14+0.15)+0.15}{6}\right\} = 0.1456$$

W_{FO} = 0.1275 W_{ST} = 0.0660

W_{MH} = 0.1251 W_{TH} = 0.0580

W_{EQ} = 0.1064 W_{VO} = 0.0600

W_{EL} = 0.0877 W_{FE} = 0.0604

W_{ES} = 0.0449

W_{CS} = 0.0243

W_{CO}= 0.0413

W_{NV} = 0.0203

W_{EH} = 0.0325

Finally, the total weight factors of all the hazard groups are obtained by using Equation (5-12), as shown below:

$$WF_{FH} = \frac{w_{FH}}{\sum_{i=1}^{14} w_{FH}} = \left\{\frac{0.1456}{0.1456+0.1275+0.1251+\cdots+0.0203}\right\} = 0.1456$$

WF_{FO} = 0.1275

WF_{FE} = 0.0604

WF_{MH} = 0.1251

WF_{ES} = 0.0449

W_{EQ} = 0.1064

WF_{CO}= 0.0413

WF_{EL} = 0.0877

WF_{EH} = 0.0325

WF_{ST} = 0.0660

WF_{CS} = 0.0243

WF_{TH} = 0.0580

WF_{NV} = 0.0203

WF_{VO} = 0.0600

Once the weight factors of the hazard groups have been obtained, the overall safety risk magnitude can be calculated by Equation (6-13):

$$\text{RM}_{\text{Overall P1}} = \sum_{i=1}^{14} RM_{HG} WF_{Hazard\ group} = 2.89\times0.1456+3\times0.1275+\ldots+3.48\times0.0203$$

$$\text{RM}_{\text{Overall Building Construction Project 1}} = 3.12$$

Consequently, the overall safety risk magnitude of building construction project 1 is 3.12. The safety risk is between *Average* and *High* with confidence of 76 per cent for Average and 24 per cent for High, as shown in Table 7-12.

Table 7-12: Safety risk magnitude of hazard groups in building construction project 1

System	Hazard groups	Hazard group scores	Hazard group categories
Building construction project 1 (3.12, Average: 76%, High: 24%)	Falls from height	2.89	Average: 100%
	Falling objects	3.00	Average: 100%
	Manual handling	3.22	Average: 56%, High: 44%
	Equipment, machinery and tools	3.44	Average: 12%, High: 88%
	Electricity	3.49	Average: 2%, High: 98%
	Slips and trips	3.00	Average: 100%
	Traffic hazards	2.76	Average: 100%
	Vehicle overturn	3.00	Average: 100%
	Fire and explosions	3.32	Average: 36%, High: 64%
	Exposure to hazardous substances	3.00	Average: 100%
	Collapse of site structure	2.79	Average: 100%
	Confined space	3.28	Average: 44%, High: 56%
	Ergonomic/Human factors	3.00	Average: 100%
	Noise and vibration	3.48	Average: 4%, High: 96%

7.2.10 Calculation of the Safety Risk Rankings

Based on the ranking of safety risks in the construction projects from highest to lowest based on the outcomes of the risk assessment, the FTOPSIS method is used to obtain the final ranking for evaluating important safety risks. The details of the aggregated STFN matrix of PO, SC and PC for all 14 hazard groups are presented in Table 7-13. As mentioned earlier, the information in the second column (PO), the third column (SC), and the fourth column (PC) is based on the experts' judgements, as shown in Table 7-13. The risks in the last column are safety risks as a function of fuzzy PO, fuzzy SC and fuzzy PC for each row.

Table 7-13: Calculation by fuzzification of the STFN of PO, SC and PC of project 1

Hazard groups	Probability of occurrence	Aggregated STFN Severity of consequence	Probability of consequence	Risks=PO× PC × SC
FH	3.40, 3.40, 3.84, 3.84	4.06, 4.06, 4.32, 4.32	4.40, 4.40, 4.40, 4.40	60.74, 60.74, 66.15, 66.15
FO	2.78, 2.78, 2.78, 2.90	3.48, 3.48, 3.74, 3.74	3.70, 3.70, 3.80, 3.80	35.80, 35.80, 39.51, 41.21
MH	2.76, 2.92, 3.02, 3.18	3.66, 3.82, 3.92, 4.08	3.26, 3.26, 3.36, 3.36	32.93, 36.36, 39.78, 43.59
EQ	3.12, 3.12, 3.38, 3.38	3.66, 3.82, 3.92, 4.08	3.48, 3.48, 3.58, 3.58	39.74, 41.48, 47.43, 49.37
EL	2.72, 2.72, 2.72, 2.72	4.22, 4.22, 4.48, 4.48	3.54, 3.54, 3.64, 3.64	40.63, 40.63, 44.36, 44.36
ST	2.60, 2.60, 2.70, 2.70	2.74, 2.74, 2.84, 2.84	3.60, 3.60, 3.70, 3.70	25.65, 25.65, 28.37, 28.37
TH	1.92, 1.92, 1.92, 1.92	3.02, 3.02, 3.02, 3.02	3.02, 3.02, 3.02, 3.02	17.51, 17.51, 17.51, 17.51
VO	2.26, 2.26, 2.36, 2.36	3.84, 3.84, 3.84, 3.84	2.76, 2.76, 2.76, 2.76	23.95, 23.95, 25.01, 25.01
FE	3.12, 3.12, 3.28, 3.28	3.78, 3.78, 4.04, 4.04	3.58, 3.58, 3.58, 3.58	42.22, 42.22, 47.44, 47.44
ES	2.56, 2.56, 2.74, 2.74	3.32, 3.32, 3.42, 3.42	3.50, 3.50, 3.50, 3.50	29.75, 29.75, 32.80, 32.80
CO	2.30, 2.30, 2.40, 2.40	3.74, 3.90, 4.00, 4.16	3.14, 3.14, 3.14, 3.14	27.01, 28.17, 30.14, 31.35
EH	2.84, 2.84, 2.94, 2.94	2.98, 3.14, 3.24, 3.40	3.42, 3.42, 3.52, 3.52	28.94, 30.50, 33.53, 35.19
CS	3.34, 3.34, 3.60, 3.60	3.56, 3.72, 3.72, 3.88	3.14, 3.14, 3.14, 3.14	37.34, 39.01, 42.05, 43.86
NV	3.20, 3.36, 3.46, 3.62	3.00, 3.16, 3.36, 3.52	4.50, 4.50, 4.60, 4.60	43.20, 47.78, 53.48, 58.62

Using Equation (5-14), the normalised matrix of fuzzy decision is obtained, as illustrated in Table 7-14. The next step is to obtain a fuzzy weighted and normalised decision matrix by utilising weights calculated by MFAHP. The fuzzy weighted and normalised decision matrix is obtained by using Equation (5-15), as shown in Table 7-14.

Based on the STFN presented in Table 7-14, the fuzzy positive ideal solution (A^{+}) by using Equation (5-16) and the fuzzy negative ideal solution (A^{-}) by using Equation (5-17) are determined as (0.134, 0.134, 0.146, 0.146) and (0.013, 0.014, 0.015, 0.015) respectively. Then, the distance of each risk from the fuzzy positive ideal solution (d^{+}) and the fuzzy negative ideal solution (d^{-}) is computed using Equations (5-18) and (5-19) respectively. Finally, a preference order can be ranked according to the order of the CC_i^* index, as shown in Table 7-14.

Once the hazard groups have been identified and evaluated, proper safety risk mitigation and control strategies must be provided to manipulate the potential safety risks in building construction project 1. According to the results of the risk ranking obtained. FH, FO, MH, EQ and EL are high-risk hazard groups and need the most attention, while NV, EH, TH and CS are low-risk hazard groups.

7.2.11 Safety Risk Controls and Discussions

According to the results of the proposed model obtained from this research, as shown in Table 7-14, hazard groups FH, FO, MH, EQ and EL are high-ranking hazard groups and need the most consideration. Conversely, hazard groups NV, EH and TH are low-ranking hazard groups. The ranking of the contributions of all 14 hazard groups in building construction project 1 in Table 7-14, is presented in Figure 7-9.

Table 7-14: Calculation of fuzzy closeness coefficient for each hazard group in building construction project 1

Hazard groups	Normalised fuzzy	Weighted normalised	*d+*	*d-*	CC_i^*	*Rank*
FH	0.918, 0.918, 1.000, 1.000	0.134, 0.134, 0.146, 0.146	0.0000	0.2504	1.0000	1
FO	0.541, 0.541, 0.597, 0.623	0.069, 0.069, 0.076, 0.079	0.1326	0.1179	0.4706	2
MH	0.498, 0.550, 0.601, 0.659	0.062, 0.069, 0.075, 0.082	0.1352	0.1160	0.4618	3
EQ	0.601, 0.627, 0.717, 0.746	0.064, 0.067, 0.076, 0.079	0.1362	0.1146	0.4569	4
EL	0.614, 0.614, 0.671, 0.671	0.054, 0.054, 0.059, 0.059	0.1668	0.0836	0.3339	5
ST	0.388, 0.388, 0.429, 0.429	0.026, 0.026, 0.028, 0.028	0.2256	0.0248	0.0990	7
TH	0.265, 0.265, 0.265, 0.265	0.015, 0.015, 0.015, 0.015	0.2489	0.0023	0.0093	13
VO	0.362, 0.362, 0.378, 0.378	0.022, 0.022, 0.023, 0.023	0.2352	0.0153	0.0611	8
FE	0.638, 0.638, 0.717, 0.717	0.039, 0.039, 0.043, 0.043	0.1977	0.0528	0.2107	6
ES	0.450, 0.450, 0.496, 0.496	0.020, 0.020, 0.022, 0.022	0.2371	0.0133	0.0531	9
CO	0.408, 0.426, 0.456, 0.474	0.017, 0.018, 0.019, 0.020	0.2432	0.0073	0.0290	10
EH	0.438, 0.461, 0.507, 0.532	0.014, 0.015, 0.016, 0.017	0.2481	0.0025	0.0098	12
CS	0.564, 0.590, 0.636, 0.663	0.014, 0.014, 0.015, 0.016	0.2498	0.0008	0.0033	14
NV	0.653, 0.722, 0.808, 0.886	0.013, 0.015, 0.016, 0.018	0.2483	0.0029	0.0114	11

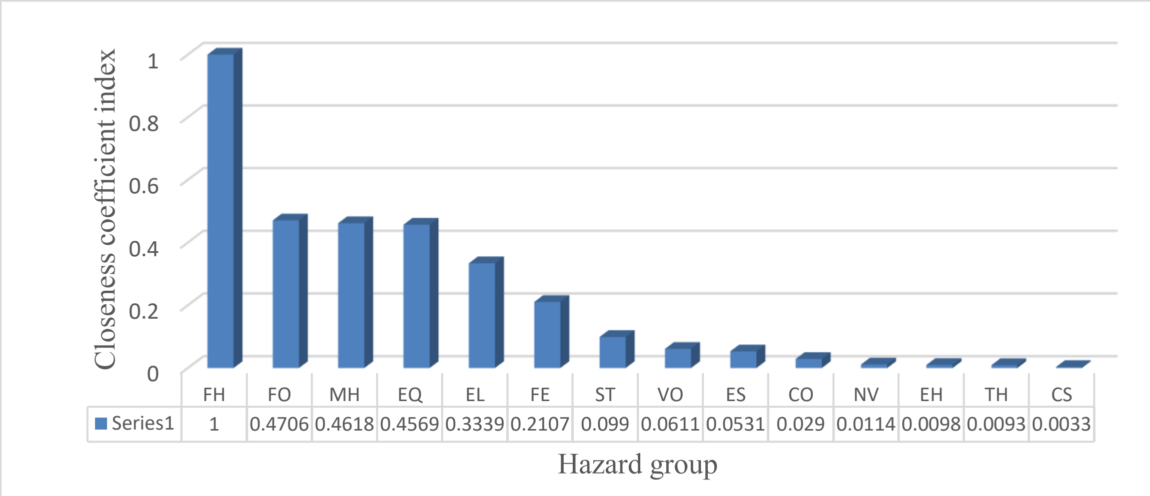


Figure 7-9: Ranking of all hazard groups in building construction project 1 to CC_i^* index

Recommended measures for each hazard group with the most important safety risk are presented and discussed below.

Falls from height are of significant concern because of the serious consequences of workers' fall injuries. This group has eight hazardous events: working platform, placement ladder, erection of scaffolding, climbing cranes, temporary ladder, hole in the ground, working on height unprotected, and through opening elevator shaft. In this situation, the probability of occurrence is mitigated significantly by following the working procedure determined by the manufacturer. Safety training and instruction on using devices providing fall protection to the workers, such as strict enforcement of the use of full harnesses and fall-arresting devices, need control to maintain safe access to the workplaces, Furthermore, experienced and competent workers should be engaged for the task, and a competent person to select or design of the suitable anchorage points for fixing the independent safe line should be appointed. Finally, warning notices should be displayed in workplaces to remind workers to follow the safety procedure.

The hazard group falling objects has seven hazardous events: part of climbing cranes and scaffolds; operating, cleaning and clearing; blown by wind; hand-held tools; hopper and bucket; stacked items; and objects under pressure or tension. To reduce the risk magnitude of falling objects, lifting paths should be demarcated, warning signs or notices should be displayed, and suitable training on safe stacking and rigging of materials should be provided for workers. Moreover, the lifting appliances and lifting gear should be examined and tested by registered professional engineers and the certificates should be valid. Furthermore, a visual inspection of the lifting gears should be carried out before using it to ensure that it is in a suitable condition and safe to use. Training on safe use of lifting appliances and lifting gear should be provided for operators and workers. Toe boards or similar safety measures should be erected near the floor edge. Warning notices should be displayed to remind other workers entering the affected areas, and the wearing of safety helmets on site should be enforced.

The manual handling group has two hazardous events: using hoists and mobile crane lifting. Adequate machines to assist in the handling of material should be provided if possible, and the wearing of suitable protective gloves by workers should be enforced. A manual handling risk assessment should be conducted by a competent person where appropriate. Instruction should be provided, and close monitoring should be carried out by a competent supervisor.

Even if the hazard groups noise and vibration, ergonomic/human factors, and traffic hazards pose the fewest hazards, inspection and control of the hazardous events in these groups should still be maintained. For example, the noise and vibration hazard group has five hazardous events: piling, excavation, hammering, vibrator machine, and hand-held power tools. Therefore, retro-fitting existing equipment with damping materials and mufflers can be carried out to reduce noise levels, and barriers can be constructed from commercial panels which are lined with sound-absorbing material to achieve the maximum shielding effect possible. Moreover, administrative control to reduce workers' noise exposure should be maintained. For example, the number of site workers exposed should be transferred from high exposure work to a lower exposure work, which could make the workers' daily noise exposure acceptable.

The results using the proposed construction safety risk management model were compared with the method developed by building construction project 1, as shown in Table 7-15. The results show that the safety risk ranking in the proposed construction safety risk management model is slightly different from the method developed by building construction project 1. For example, in the proposed model, falls from height (working on height unprotected) has the highest safety risk score of 4.27 and type of safety risk has confidence of 54 per cent for High and 46 per cent for Unacceptable. Furthermore, the results show that working at height unprotected, hammering, electrical work, through opening elevator shaft and heavy equipment are identified as the five hazardous events with higher safety risk scores than any others in both building construction project 1's method and the proposed model. Obviously, the results from the building construction project 1's method can only produce similar safety risk level results and cannot provide both risk level and type of safety risk with a confidence percentage. Therefore, the overall the safety risk of the project and safety risk ranking can support construction project staff for mitigation and controlling safety risks in order to improve the SSOP during the construction projects. It can be concluded that the proposed construction safety risk management model is a reliable and less ambiguous methodology for management of critical hazards and dealing with uncertainties affecting the safety of construction projects.

Table 7-15: Safety risk level of building construction project 1

Proposed Construction Safety Risk Management Method			Building Construction Project 1's Method
Hazardous events	Safety risk score	Safety risk categories	Risk level
FH-07 Working on height unprotected	4.27	High: 54%, Unacceptable 46%	High
NV-53 Hammering	3.67	High 100%	High
EL-22 Electrical work	3.63	High 100%	High
FH-08 Through opening elevator shaft	3.50	High 100%	High
EQ-18 Heavy equipment	3.50	High 100%	High
FE-36 Gas cylinder or hose leakage	3.48	Average: 4%, High: 96%	High
MH-17 Mobile crane lifting	3.37	Average: 26%, High: 74%	High
CS-47 Closed tanks	3.28	Average: 44%, High: 56%	High
NV-51 Piling	3.26	Average: 48%, High: 52%	High
FE-35 Working near flammables	3.22	Average: 56%, High: 44%	High
FE-34 Hot work	3.10	Average: 80%, High: 20%	High
FH-03 Erection of scaffolding	3.00	Average: 100%	High
FH-04 Climbing cranes	3.00	Average: 100%	High
FH-06 Hole in the ground	3.00	Average: 100%	High
FO-09 Part of climbing cranes, scaffolds	3.00	Average: 100%	High
FO-10 Operating, cleaning and clearing	3.00	Average: 100%	Medium
FO-11 Blown by wind	3.00	Average: 100%	Medium
FO-12 Hand-held tools	3.00	Average: 100%	Medium
FO-13 Hopper and bucket	3.00	Average: 100%	Medium
FO-14 Stacked items	3.00	Average: 100%	Medium
FO-15 Objects under pressure or tension	3.00	Average: 100%	Medium
MH-16 Hoists	3.00	Average: 100%	Medium
EQ-19 Steel bar bending machine	3.00	Average: 100%	Medium
EQ-20 Vibrator machine	3.00	Average: 100%	Medium
EL-21 Wires	3.00	Average: 100%	Medium
EL-23 Overhead power lines	3.00	Average: 100%	Medium
EL-24 Arc welding machine	3.00	Average: 100%	Medium
ST-25 Tripping over building materials	3.00	Average: 100%	Medium
ST-26 Slipping on wet surfaces	3.00	Average: 100%	Medium

Proposed Construction Safety Risk Management Method			Building Construction Project 1's Method
Hazardous events	Safety risk score	Safety risk categories	Risk level
ST-27 Trips caused by small change	3.00	Average: 100%	Medium
ST-29 Walking around construction site	3.00	Average: 100%	Medium
VO-32 Crane overturn	3.00	Average: 100%	High
VO-33 Mobile plant (Bobcat, tractor)	3.00	Average: 100%	Medium
FE-37 Fire extinguisher has been discharged	3.00	Average: 100%	Medium
ES-38 Solvents	3.00	Average: 100%	Medium
ES-39 Cement dust	3.00	Average: 100%	Medium
ES-40 Corrosive substances	3.00	Average: 100%	Medium
CO-41 Collapse of boom (cranes)	3.00	Average: 100%	High
CO-42 Collapse of scaffolding	3.00	Average: 100%	High
CO-44 Steel sheet piles	3.00	Average: 100%	Medium
CO-45 Kingpost	3.00	Average: 100%	Medium
CS-46 Deep excavations	3.00	Average: 100%	Medium
EH-48 Poor work posture	3.00	Average: 100%	Medium
EH-49 Repetitive movement	3.00	Average: 100%	Medium
EH-50 Extreme muscular exertion	3.00	Average: 100%	Medium
NV-52 Excavation	3.00	Average: 100%	Medium
NV-54 Vibrator machine	3.00	Average: 100%	Medium
CO-43 Temporary structure	2.79	Average: 100%	Medium
TH-30 Collision with another vehicle	2.76	Average: 100%	Medium
TH-31 Collision with plant/people	2.76	Average: 100%	Medium
FH-02 Placement ladder	2.72	Average: 100%	Medium
NV-55 Hand-held power tools	2.66	Average: 100%	Medium
FH-01 Working platform	2.61	Average: 100%	High
FH-05 Temporary ladder	2.10	Average: 100%	Low

7.3 Case Study 2: Building Construction Project

7.3.1 Background of Case Study 2

"Building Construction Company 2" is used instead of the building construction company's name due to business confidentiality. The company undertakes construction projects in the private and public sectors. It provides customers with a comprehensive range of services covering the whole project development process, including from preliminary development and market analysis, marketing, finance, engineering, operation, design, and maintenance. This construction project is a condominium project in Bangkok, Thailand. The condominium comprises three buildings, with 50 floors and 1,442 units.

7.3.2 Establishing a Safety Risk Management Team

Five experts involved in the safety risk management model were selected based on their individual skills, knowledge, experience, and expertise. One expert is a project manager who has worked on building construction project for more than 19 years. Two experts are production managers with 23 years' experience in building construction projects. The other experts are a quality assurance (QA) officer and a safety officer, as shown in Table 7-16

Table 7-16: Description of experts' contribution factors for building construction project 2

Expert	Title of expert	Score	Years of experience	Score	Weighting score	Weighting factor
Expert 1	Project Manager	5	19	5	10	0.25
Expert 2	Production Manager	5	23	5	10	0.25
Expert 3	Production Manager	5	23	5	10	0.25
Expert 4	QA Officer	2	7	3	5	0.125
Expert 5	Safety Officer	2	9	3	5	0.125

7.3.3 Safety Hazard Identification

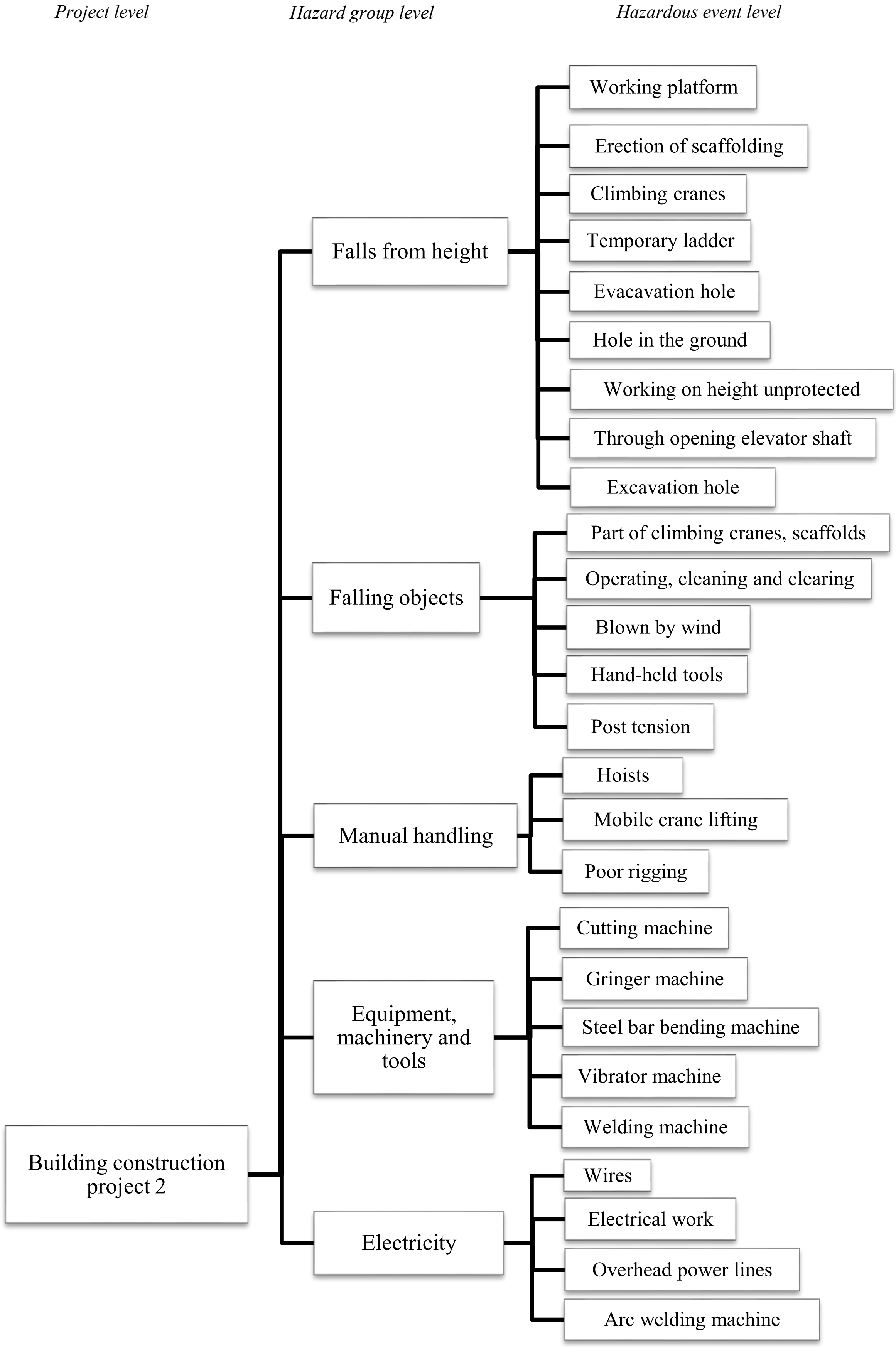
To carry out safety risk assessment and management, hazard identification by using brainstorming and discussions with the safety risk management team of building construction project 2, information was gathered and verified to identify all the hazard groups and hazardous events. The building construction safety system is divided into 13 hazard groups: falls from height; falling objects; manual handling; equipment machinery and tools; electricity; slips and trips; traffic hazards; fire and explosions; exposure to hazardous substances; collapse of site structure; confined space; ergonomic/human factors; and noise and vibration. Each hazard group includes several of identified safety risk events and is described below and shown in Figure 7-10.

(1) *Falls from height* includes nine hazardous events: working platform (FH-001), erection of scaffolding (FH-002,) climbing cranes (FH-003), temporary ladder (FH-004), hole in the ground (FH-005), working on height unprotected (FH-006), through opening elevator shaft (FH-007), working formwork (FH-008), and excavation hole (FH-009).

(2) *Falling objects* includes five hazardous events: part of climbing cranes, scaffolds (FO-010), operating, cleaning and clearing (FO-011), hand-held tools (FO-012), post-tension (FO-013), and blown by wind (FO-014).

(3) *Manual handling* includes tree hazardous events: hoists (MH-015), poor rigging (MH-016), and mobile crane lifting (MH-017).

(4) *Equipment machinery and tools* includes five hazardous events: cutting machine (EQ-018), steel bar bending machine (EQ-019), grinder machine (EQ-020), welding machine (EQ-021), and concrete breaking machine (EQ-022).


Project level
Hazard group level
Hazardous event level
Building construction project 2
Falls from height
Working platform
Erection of scaffolding
Climbing cranes
Temporary ladder
Evacavation hole
Hole in the ground
Working on height unprotected
Through opening elevator shaft
Excavation hole
Falling objects
Part of climbing cranes, scaffolds
Operating, cleaning and clearing
Blown by wind
Hand-held tools
Post tension
Manual handling
Hoists
Mobile crane lifting
Poor rigging
Equipment, machinery and tools
Cutting machine
Gringer machine
Steel bar bending machine
Vibrator machine
Welding machine
Electricity
Wires
Electrical work
Overhead power lines
Arc welding machine

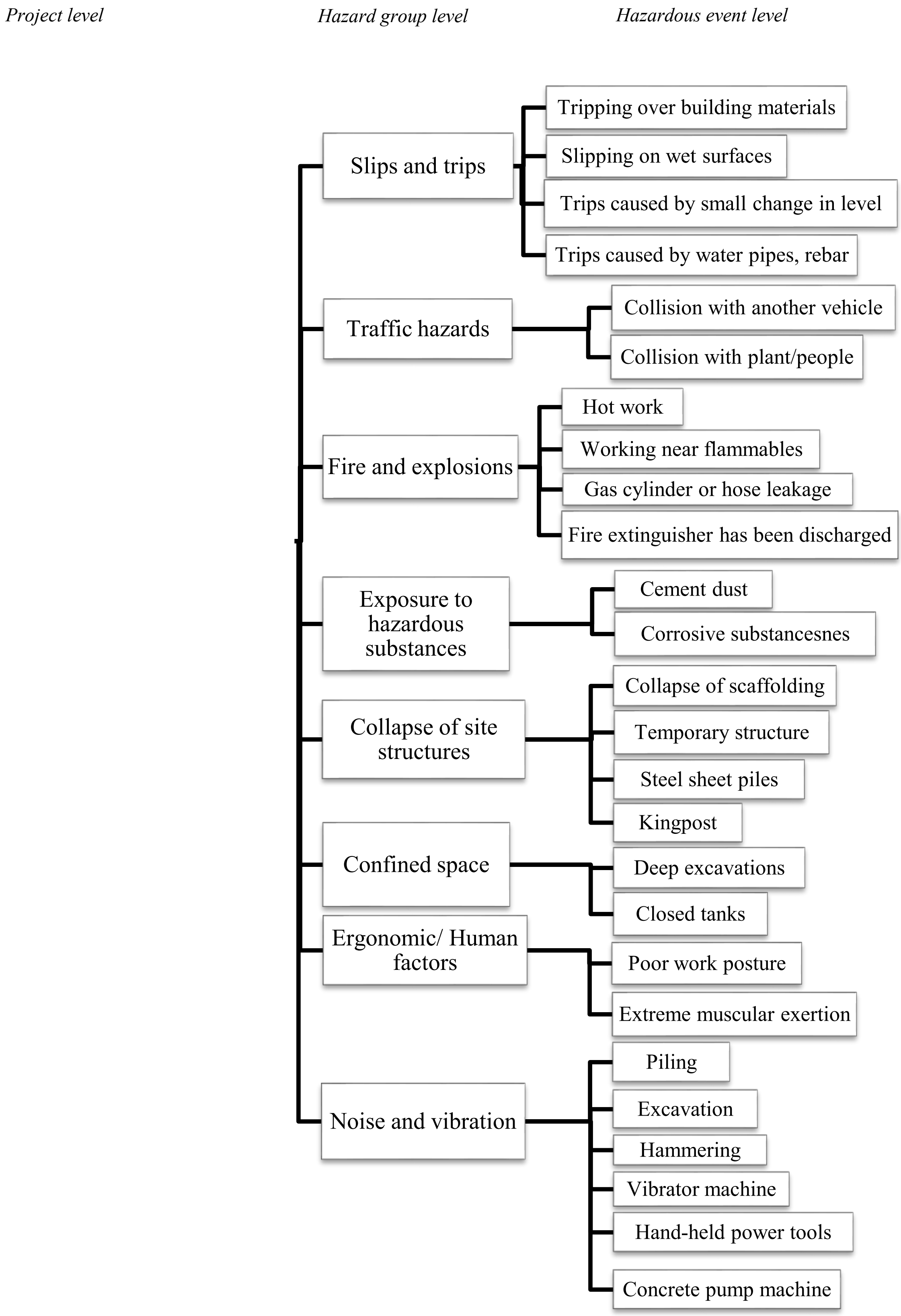


Figure 7-10: Hazard identification at building construction project 2

(5) *Electricity* includes four hazardous events: wires (EL-023), electrical work (EL-024), overhead power lines (EL-025), and arc welding machine (EL-026).

(6) *Slips and trips* includes four hazardous events: tripping over building materials (ST-027), slipping on wet surfaces (ST-028), trips caused by small change in level (ST-029), and trips caused by water pipes, rebar (ST-030)

(7) *Traffic hazards* includes two hazardous events: collision with another vehicle (TH-031), and collision with plant/people (TH-032).

(8) *Fire and explosions* includes four hazardous events: hot work (FE-033), working near flammables (FE-034), gas cylinder or hose leakage (FE-035), and fire extinguisher has been discharged (FE-036).

(9) *Exposure to hazardous substances* includes two hazardous events: cement dust (ES-037), and corrosive substances (ES-038).

(10) *Collapse of site structure* includes four hazardous events, i.e. collapse of boom (cranes) (CO-039), collapse of scaffolding (CO-040), steel sheet piles (CO-041), and kingpost (CO-042).

(11) *Confined space* includes two hazardous events: deep excavations (CS-043), and closed tanks (CS-044).

(12) *Ergonomic and human factors* includes two hazardous events: poor work posture (EH-045), and extreme muscular exertion (EH-046).

(13) *Noise and vibration* includes six hazardous events: piling (NV-047), excavation (NV-048), hammering (NV-049), vibrator machine (NV-050), hand-held power tools (NV-051), and concrete pump machine (NV-052).

7.3.4 Safety Risk Estimation

As the safety risk management process of building construction project 2 is similar to the case study on safety risk management of building construction project 1, the linguistic variables of the all risk parameters, PC, PO and SC and the fuzzy rule base were employed in this case. Once safety risk criteria were established and the data on PO, SC and PC had been calculated by using fuzzification, fuzzy aggregation, fuzzy inference, and defuzzification, the safety risk magnitude of all the hazardous events of building construction project 2 could be obtained as shown in Table 7-17.

For instance, it can be seen in Table 7-17 that FH-003 (Climbing cranes) has aggregated STFN of 1.00, 1.00, 1.00 and 1.00 of PO, and 3.75, 3.75, 3.75, and 3.75 of SC, and 1.75, 1.75, 1.75, and 1.75 of PC. After fuzzy inference, the matching fuzzy set of PO was evaluated as "Unlikely" with a membership function value of 1.00. SC was evaluated as "Major" with a membership function value of 1.00. PC was evaluated as "Unlikely" with a membership function value of 0.50 and "Reasonably unlikely" with a membership function value of 0.50. However, two rules were fired, contributing to the assessment procedure.

These two rules are: "Rule#98: *IF PO is Unlikely and SC is Major and PC is Unlikely, THEN RM is Acceptable"* and "Rule#99: *IF PO is Unlikely and SC is Major and PC is Reasonably unlikely, THEN RM is Average*".

Table 7-17: Safety risk magnitude of building construction project 2

Hazard groups	Hazardous events	Aggregated STFN Probability of occurrence	Severity of consequence	Probability of consequence	Safety risk score	Safety risk categories
Falls from height	FH-001 Working platform	1.00, 1.00, 1.00, 1.00	2.75, 2.75, 3.25, 3.25	2.25, 2.25, 2.25, 2.25	2.00	Average: 100%
	FH-002 Erection of scaffolding	1.00, 1.00, 1.00, 1.00	2.25, 2.25, 2.75, 2.75	2.50, 2.50, 2.50, 2.50	1.50	Acceptable: 100%
	FH-003 Climbing cranes	1.00, 1.00, 1.00, 1.00	3.75, 3.75, 3.75, 3.75	1.75, 1.75, 1.75, 1.75	2.25	Average: 100%
	FH-004 Temporary ladder	1.00, 1.00, 1.00, 1.00	3.13, 3.13, 3.13, 3.13	2.25, 2.25, 2.25, 2.25	1.89	Acceptable: 22%, Average: 78 %
	FH-005 Hole in the ground	1.25, 1.25, 1.25, 1.25	3.50, 3.50, 3.75, 3.75	3.00, 3.00, 3.00, 3.00	3.00	Average: 100%
	FH-006 Working on height unprotected	2.38, 2.38, 2.38, 2.38	3.13, 3.13, 3.38, 3.38	3.25, 3.25, 3.25, 3.25	3.00	Average: 100%
	FH-007 Through opening elevator shaft	1.00, 1.00, 1.00, 1.00	3.50, 3.50, 3.75, 3.75	2.13, 2.13, 2.13, 2.13	3.00	Average: 100%
	FH-008 Working formwork	1.00, 1.00, 1.00, 1.00	3.00, 3.00, 3.00, 3.00	2.50, 2.50, 2.50, 2.50	1.50	Acceptable: 100%
	FH-009 Excavation hole	1.13, 1.13, 1.13, 1.13	3.38, 3.38, 3.38, 3.38	2.13, 2.13, 2.13, 2.13	2.64	Average: 100%
Falling objects	FO-010 Part of climbing cranes, scaffolds	1.50, 1.50, 1.50, 1.50	2.88, 3.13, 3.38, 3.63	2.50, 2.50, 2.50, 2.50	2.26	Average: 100%
	FO-011 Operating, cleaning and clearing	2.63, 2.63, 2.75, 2.75	2.75, 3.00, 3.00, 3.25	2.88, 2.88, 2.88, 2.88	3.00	Average: 100%
	FO-012 Hand-held tools	1.88, 1.88, 2.00, 2.00	2.13, 2.13, 2.38, 2.38	3.00, 3.00, 3.00, 3.00	2.71	Average: 100%
	FO-013 Post-tension	1.00, 1.00, 1.00, 1.00	3.75, 3.75, 4.25, 4.25	1.88, 1.88, 1.88, 1.88	2.64	Average: 100%
	FO-014 Blown by wind	2.25, 2.25, 2.25, 2.25	2.38, 2.38, 2.38, 2.38	2.38, 2.38, 2.38, 2.38	3.00	Average: 100%
Manual handling	MH-015 Hoists	1.63, 1.63, 1.63, 1.63	2.25, 2.25, 2.50, 2.50	2.38, 2.38, 2.38, 2.38	1.89	Acceptable: 22%, Average: 78 %
	MH-016 Poor rigging	1.75, 1.75, 1.75, 1.75	2.00, 2.00, 2.00, 2.00	2.63, 2.63, 2.63, 2.63	2.25	Average: 100%
	MH-017 Mobile crane lifting	1.63, 1.63, 1.63, 1.63	1.88, 1.88, 1.88, 1.88	2.63, 2.63, 2.63, 2.63	1.89	Acceptable: 22%, Average: 78 %
Equipment, machinery and tools	EQ-018 Cutting machine	1.25, 1.25, 1.25,1.25	2.38, 2.38, 2.88, 2.88	2.13, 2.13, 2.13, 2.13	1.50	Acceptable: 100%
	EQ-019 Steel bar bending machine	1.50, 1.50, 1.50, 1.50	2.38, 2.38, 2.63, 2.63	2.50, 2.50, 2.50, 2.50	1.50	Acceptable: 100%
	EQ-020 Grinder machine	1.75, 1.75, 1.75, 1.75	3.00, 3.00, 3.50, 3.50	2.88, 2.88, 2.88, 2.88	2.25	Average: 100%
	EQ-021 Welding machine	1.88, 1.88, 1.88, 1.88	2.50, 2.50, 2.75, 2.75	2.25, 2.25, 2.25, 2.25	2.64	Average: 100%
	EQ-022 Concrete breaking machine	1.88, 1.88, 1.88, 1.88	2.25, 2.25, 2.50, 2.50	2.63, 2.63, 2.63, 2.63	2.64	Average: 100%
Electricity	EL-023 Wires	1.88, 1.88, 1.88, 1.88	2.63, 2.63, 2.88, 2.88	2.50, 2.50, 2.50, 2.50	2.64	Average: 100%
	EL-024 Electrical work	1.75, 1.75, 1.75, 1.75	2.50, 2.50, 2.50, 2.50	2.63, 2.63, 2.63, 2.63	2.25	Average: 100%
	EL-025 Overhead power lines	1.50, 1.50, 1.50, 1.50	2.25, 2.25, 2.25, 2.25	1.75, 1.75, 1.75, 1.75	1.50	Acceptable: 100%
	EL-026 Arc welding machine	2.13, 2.13, 2.13, 2.13	2.63, 2.63, 2.63, 2.63	2.25, 2.25, 2.25, 2.25	3.00	Average: 100%
Slips and trips	ST-027 Tripping over building materials	2.25, 2.25, 2.25, 2.25	1.75, 1.75, 2.00, 2.00	3.38, 3.38, 3.38, 3.38	2.64	Average: 100%
	ST-028 Slipping on wet surfaces	1.75, 1.75, 1.75, 1.75	2.25, 2.25, 2.50, 2.50	3.25, 3.25, 3.25, 3.25	2.25	Average: 100%
	ST-029 Trips caused by small change	2.25, 2.25, 2.25, 2.25	2.13, 2.13, 2.13, 2.13	3.63, 3.63, 3.63, 3.63	3.00	Average: 100%
	ST-030 Trips caused by water pipes	2.13, 2.13, 2.13, 2.13	1.88, 1.88, 1.88, 1.88	3.63, 3.63, 3.63, 3.63	3.00	Average: 100%

Hazard groups	Hazardous events	Probability of occurrence	Aggregated STFN Severity of consequence	Probability of consequence	Safety risk scores	Safety risk categories
Traffic hazards	TH-031 Collision with another vehicle	2.25, 2.25, 2.25, 2.25	2.00, 2.00, 2.00, 2.00	2.75, 2.75, 2.75, 2.75	3.00	Average: 100%
	TH-032 Collision with plant/people	2.00, 2.00, 2.00, 2.00	2.63, 2.63, 2.63, 2.63	2.75, 2.75, 2.75, 2.75	3.00	Average: 100%
Fire and explosions	FE-033 Hot work	3.00, 3.00, 3.00, 3.00	2.50, 2.50, 2.75, 2.75	3.13, 3.13, 3.13, 3.13	3.00	Average: 100%
	FE-034 Working near flammables	2.38, 2.38, 2.38, 2.38	2.88, 2.88, 3.13, 3.13	3.13, 3.13, 3.13, 3.13	3.00	Average: 100%
	FE-035 Gas cylinder or hose leakage	2.00, 2.00, 2.00, 2.00	2.38, 2.38, 2.38, 2.38	2.88, 2.88, 2.88, 2.88	3.00	Average: 100%
	FE-036 Fire extinguisher has been discharged	2.75, 2.75, 2.75, 2.75	2.38, 2.38, 2.38, 2.38	2.25, 2.25, 2.25, 2.25	3.00	Average: 100%
Exposure to hazardous substances	ES-037 Cement dust	2.50, 2.50, 2.50, 2.50	2.25, 2.25, 2.25, 2.25	3.50, 3.50, 3.50, 3.50	3.00	Average: 100%
	ES-038 Formwork striking oil, epoxy	1.63, 1.63, 1.63, 1.63	1.75, 1.75, 1.75, 1.75	3.00, 3.00, 3.00, 3.00	2.01	Average: 100%
Collapse of site structure	CO-039 Temporary structure	1.25, 1.25, 1.25, 1.25	3.75, 3.75, 4.25, 4.25	1.63, 1.63, 1.63, 1.63	2.10	Average: 100%
	CO-040 Collapse of scaffolding	1.13, 1.13, 1.13, 1.13	3.63, 3.88, 4.13, 4.38	1.75, 1.75, 1.75, 1.75	2.25	Average: 100%
	CO-041 Steel sheet piles	1.00, 1.00, 1.00, 1.00	3.75, 4.00, 4.25, 4.50	1.25, 1.25, 1.25, 1.25	2.10	Average: 100%
	CO-042 Kingpost	1.00, 1.00, 1.00, 1.00	3.75, 4.00, 4.25, 4.50	1.25, 1.25, 1.25, 1.25	2.10	Average: 100%
Confined space	CS-043 Deep excavations	1.25, 1.25, 1.25, 1.25	3.75, 4.00, 4.25, 4.50	2.00, 2.00, 2.00, 2.00	3.00	Average: 100%
	CS-044 Closed tanks	1.00, 1.00, 1.00, 1.00	3.75, 4.00, 4.00, 4.25	1.75, 1.75, 1.75, 1.75	2.00	Average: 100%
Ergonomic / Human factors	EH-045 Poor work posture	2.13, 2.13, 2.13, 2.13	2.50, 2.50, 2.50, 2.50	3.75, 3.75, 3.75, 3.75	3.00	Average: 100%
	EH-046 Extreme muscular exertion	2.38, 2.38, 2.38, 2.38	2.50, 2.50, 2.75, 2.75	3.50, 3.50, 3.50, 3.50	3.00	Average: 100%
Noise and vibration	NV-047 Piling	1.38, 1.38, 1.38, 1.38	2.13, 2.13, 2.13, 2.13	2.25, 2.25, 2.25, 2.25	1.50	Acceptable: 100%
	NV-048 Excavation	1.38, 1.38, 1.38, 1.38	2.63, 2.63, 2.63, 2.63	2.25, 2.25, 2.25, 2.25	1.50	Acceptable: 100%
	NV-049 Hammering	1.25, 1.25, 1.25, 1.25	2.75, 2.75, 2.75, 2.75	2.25, 2.25, 2.25, 2.25	1.50	Acceptable: 100%
	NV-050 Vibrator machine	1.13, 1.13, 1.13, 1.13	2.00, 2.00, 2.00, 2.00	2.00, 2.00, 2.00, 2.00	1.50	Acceptable: 100%
	NV-051 Hand-held power tools	1.13, 1.13, 1.13, 1.13	1.63, 1.63, 1.63, 1.63	2.00, 2.00, 2.00, 2.00	1.50	Acceptable: 100%
	NV-052 Concrete pump machine	1.88, 1.88, 1.88, 1.88	2.38, 2.38, 2.38, 2.38	3.00, 3.00, 3.00, 3.00	2.64	Average: 100%

The firing strength in this case can be obtained by:

- $Rule$ #98 : $\mu\, UN(PO) \cap \mu MA(SC) \cap \mu UN(PC) = min(1.00, 1.00,\ 0.50) = 0.50$
- $Rule$ #99 : $\mu\, UN(PO) \cap \mu MA(SC) \cap \mu RU(PC) = min(1.00,\ 1.00,\ 0.50) = 0.50$

Therefore, $Rule$ #98 has a firing strength of 0.50 with a safety risk category of "Acceptable", and $Rule$ #99 has a firing strength of 0.50 with a safety risk category of "Average". Using Equations (6-2) and (6-3), the output fuzzy membership function after aggregation and the final results of the defuzzification could be obtained as shown in Table 7-17.

To validate the proposed construction safety risk analysis model's results, the results obtained from the traditional two parameters (2Ps) were compared with those obtained from the proposed model, as shown in Table 7-18. In this table, the safety risk magnitude values for both parameters and the proposed model in which three parameters have been calculated based on the safety risk assessment methodology using the FRT are slightly different. The overall results have been affected by probability of consequence when the hazardous event with very low probability of occurrence but severity of consequence still very high than the probability of consequence or with very high probability of consequence but probability of occurrence and severity of consequence very low.

7.3.5 Safety Risk Ranking

To assess the overall safety risk magnitude of construction project 2, the MFAHP based on trapezoidal fuzzy number was used to obtain the weighting factor of each hazard group. Experts were asked to make pairwise comparisons of all hazard groups, and all aggregated pairwise comparison values were calculated, as shown in Table 7-19. A pairwise matrix based on experts' judgements was constructed and an MFAHP preference relation decision matrix was established, as shown in Table 7-20.

Table 7-18: Safety risk magnitude when compared with two parameters (2Ps) in project 2

Hazard groups	Hazardous event codes	Safety risk scores (2Ps)	Safety risk categories	Safety risk scores (3Ps)	Safety risk categories
Falls from height	FH-001	2.00	Average: 100%	2.00	Average: 100%
	FH-002	1.50	Acceptable: 100%	1.50	Acceptable: 100%
	FH-003	1.50	Acceptable: 100%	2.25	Average: 100%
	FH-004	1.89	Acceptable: 22%, Average: 78 %	1.89	Acceptable: 22%, Average: 78 %
	FH-005	3.00	Average: 100%	3.00	Average: 100%
	FH-006	3.00	Average: 100%	3.00	Average: 100%
	FH-007	3.00	Average: 100%	3.00	Average: 100%
	FH-008	1.50	Acceptable: 100%	1.50	Acceptable: 100%
	FH-009	2.64	Average: 100%	2.64	Average: 100%
Falling objects	FO-010	2.26	Average: 100%	2.26	Average: 100%
	FO-011	3.00	Average: 100%	3.00	Average: 100%
	FO-012	2.71	Average: 100%	2.71	Average: 100%
	FO-013	2.00	Average: 100%	2.64	Average: 100%
	FO-014	3.00	Average: 100%	3.00	Average: 100%
Manual handling	MH-015	1.89	Acceptable: 22%, Average: 78 %	1.89	Acceptable: 22%, Average: 78 %
	MH-016	2.25	Average: 100%	2.25	Average: 100%
	MH-017	1.89	Acceptable: 22%, Average: 78 %	1.89	Acceptable: 22%, Average: 78 %
Equipment, machinery and tools	EQ-018	1.50	Acceptable: 100%	1.50	Acceptable: 100%
	EQ-019	1.50	Acceptable: 100%	1.50	Acceptable: 100%
	EQ-020	2.25	Average: 100%	2.25	Average: 100%
	EQ-021	2.64	Average: 100%	2.64	Average: 100%
	EQ-022	2.64	Average: 100%	2.64	Average: 100%
Electricity	EL-023	2.64	Average: 100%	2.64	Average: 100%
	EL-024	2.25	Average: 100%	2.25	Average: 100%
	EL-025	1.50	Acceptable: 100%	1.50	Acceptable: 100%
	EL-026	3.00	Average: 100%	3.00	Average: 100%
Slips and trips	ST-027	2.50	Average: 100%	2.64	Average: 100%
	ST-028	2.25	Average: 100%	2.25	Average: 100%
	ST-029	3.00	Average: 100%	3.00	Average: 100%
	ST-030	3.00	Average: 100%	3.00	Average: 100%
Traffic hazards	TH-031	3.00	Average: 100%	3.00	Average: 100%
	TH-032	3.00	Average: 100%	3.00	Average: 100%
Fire and explosions	FE-033	3.00	Average: 100%	3.00	Average: 100%
	FE-034	3.00	Average: 100%	3.00	Average: 100%
	FE-035	3.00	Average: 100%	3.00	Average: 100%
	FE-036	3.00	Average: 100%	3.00	Average: 100%
Exposure to hazardous substances	ES-037	3.00	Average: 100%	3.00	Average: 100%
	ES-038	2.01	Average: 100%	2.01	Average: 100%
Collapse of site structure	CO-039	2.00	Average: 100%	2.10	Average: 100%
	CO-040	2.00	Average: 100%	2.25	Average: 100%
	CO-041	2.10	Average: 100%	2.10	Average: 100%
	CO-042	2.10	Average: 100%	2.10	Average: 100%
Confined space	CS-043	3.00	Average: 100%	3.00	Average: 100%
	CS-044	1.88	Average: 76% Acceptable: 24%	2.00	Average: 100%

Table 7-18: (Continued)

Hazard Groups	Hazardous Event Codes	Safety risk scores (2 Ps)	Safety Risk categories	Safety risk scores (3 Ps)	Safety Risk categories
Ergonomic / Human factors	EH-045	3.00	Average: 100%	3.00	Average: 100%
	EH-046	3.00	Average: 100%	3.00	Average: 100%
Noise and vibration	NV-047	1.50	Acceptable: 100%	1.50	Acceptable: 100%
	NV-048	1.50	Acceptable: 100%	1.50	Acceptable: 100%
	NV-049	1.50	Acceptable: 100%	1.50	Acceptable: 100%
	NV-050	1.50	Acceptable: 100%	1.50	Acceptable: 100%
	NV-051	1.50	Acceptable: 100%	1.50	Acceptable: 100%
	NV-052	2.64	Average: 100%	2.64	Average: 100%

After calculating the weights using Equations (5-5), (5-6), (5-7) and (5-8), the weight factors of all the hazard groups were obtained, as shown in Table 7-21. The overall safety risk magnitude can be calculated by Equation (6-13)

$$RM_{Overall\ P2} = \sum_{i=1}^{13} RM_{HG} WF_{Hazard\ group} = 2.25\times0.1920+2.32\times0.1347+\ldots+2.15\times0.0214$$

$$RM_{Overall\ Building\ Construction\ Project\ 2} = 2.40$$

Consequently, the overall safety risk magnitude of building construction project 2 is 2.40 and is in the *Average* category with confidence of 100 per cent, as shown in Table 7-21.

Table 7-19: Experts' judgements of building construction project 2

Comparison	*Expert 1 (0.25)*		*Expert 2 (0.25)*		*Expert 3 (0.25)*		*Expert 4 (0.125)*		*Expert 5 (0.125)*		Aggregated STFN
	Score	Converted STFN	Score	Converted STFN	Score	Converted STFN	Score	Converted STFN	Score	Converted STFN	
FH vs. FO (RH1, 2)	1.00	1.00, 1.00, 1.00, 1.00	5.00	5.00, 5.00, 5.00, 5.00	9.00	9.00, 9.00, 9.00, 9.00	1.00	1.00, 1.00, 1.00, 1.00	1.00	1.00, 1.00, 1.00, 1.00	4.00, 4.00, 4.00, 4.00
FO vs. MH (RH2, 3)	8.00	8.00, 8.00, 8.00, 8.00	5.00	5.00, 5.00, 5.00, 5.00	7.00	7.00, 7.00, 7.00, 7.00	7.00	7.00, 7.00, 7.00, 7.00	7.00	7.00, 7.00, 7.00, 7.00	6.75, 6.75, 6.75, 6.75
MH vs. EQ (RH3, 4)	1.00	1.00, 1.00, 1.00, 1.00	0.33	0.33, 0.33, 0.33, 0.33	0.14	0.14, 0.14, 0.14, 0.14	0.14	0.14, 0.14, 0.14, 0.14	0.14	0.14, 0.14, 0.14, 0.14	0.40, 0.40, 0.40, 0.40
EQ vs. EL (RH4, 5)	1.00	1.00, 1.00, 1.00, 1.00	3.00	3.00, 3.00, 3.00, 3.00	0.11	0.11, 0.11, 0.11, 0.11	0.25	0.25, 0.25, 0.25, 0.25	0.14	0.14, 0.14, 0.14, 0.14	1.08, 1.08, 1.08, 1.08
EL vs. ST (RH5, 6)	8.00	8.00, 8.00, 8.00, 8.00	5.00	5.00, 5.00, 5.00, 5.00	9.00	9.00, 9.00, 9.00, 9.00	7.00	7.00, 7.00, 7.00, 7.00	0.14	0.14, 0.14, 0.14, 0.14	6.39, 6.39, 6.39, 6.39
ST vs. TH (RH6, 7)	1.00	1.00, 1.00, 1.00, 1.00	0.20	0.20, 0.20, 0.20, 0.20	7.00	7.00, 7.00, 7.00, 7.00	4.00	4.00, 4.00, 4.00 4.00	0.20	0.20, 0.20, 0.20, 0.20	2.58, 2.58, 2.58, 2.58
TH vs. FE (RH7, 8)	0.11	0.11, 0.11,	0.20	0.20, 0.20,	0.11	0.11, 0.11	0.13	0.13, 0.13	0.11	0.11, 0.11,	0.13, 0.13,

Table 7-19: (Continued)

Comparison	*Expert 1 (0.25)*		*Expert 2 (0.25)*		*Expert 3 (0.25)*		*Expert 4 (0.125)*		*Expert 5 (0.125)*		Aggregated STFN
	Score	Converted STFN	Score	Converted STFN	Score	Convert STFN	Score	Converted STFN	Score	Converted STFN	
		0.11, 0.11,		0.20, 0.20		0.11, 0.11		0.13, 0.13		0.11, 0.11	0.13, 0.13
FE vs. ES (RH8, 9)	8.00	8.00, 8.00, 8.00, 8.00	5.00	5.00, 5.00, 5.00, 5.00	9.00	9.00, 9.00 9.00, 9.00	5.00	5.00, 5.00, 5.00, 5.00	9.00	9.00, 9.00 9.00, 9.00	7.25, 7.25, 7.25, 7.25
ES vs. CO (RH9,10)	0.11	0.11 0.11, 0.11, 0.11,	0.14	0.14, 0.14, 0.14, 0.14	7.00	7.00, 7.00, 7.00, 7.00	0.20	0.20, 0.20, 0.20, 0.20	0.20	0.20, 0.20, 0.20, 0.20	1.86, 1.86, 1.86, 1.86
CO vs. CS (RH10, 11)	1.00	1.00, 1.00, 1.00, 1.00	0.20	0.20, 0.20, 0.20, 0.20	2.00	2.00, 2.00, 2.00, 2.00	1.00	1.00, 1.00, 1.00, 1.00	1.00	1.00, 1.00, 1.00, 1.00	0.80, 0.80, 0.80, 0.80
CS vs. EH (RH11, 12)	9.00	9.00, 9.00 9.00, 9.00,	5.00	5.00, 5.00, 5.00, 5.00	9.00	9.00, 9.00 9.00, 9.00,	6.00	6.00, 6.00, 6.00, 6.00	9.00	9.00, 9.00 9.00, 9.00	7.63, 7.63, 7.63, 7.63
EH vs. NV (RH12, 13)	0.13	0.13, 0.13, 0.13, 0.13	3.00	3.00, 3.00, 3.00, 3.00	6.00	6.00, 6.00, 6.00, 6.00	1.00	1.00, 1.00, 1.00, 1.00	1.00	1.00, 1.00, 1.00, 1.00	2.53, 2.53, 2.53, 2.53

Table 7-20: MFAHP preference relation decision matrix for building construction project 2

	FH	FO	MH	EQ	EL	ST	TH	FE	ES	CO	EH	CS	NV
FH	1.00, 1.00, 1.00, 1.00	1.42, 1.42, 1.42, 1.42	2,32, 2.32, 2.32, 2.32	1.84, 1.84, 1.84, 1.84	1.88, 1.88, 1.88, 1.88	3.02, 3.02, 3.02, 3.02	3.84, 3.84, 3.84, 3.84	2.30, 2.30, 2.30, 2.30	3.82, 3.82, 3.82, 3.82	4.47, 4.47, 4.47, 4.47	4.22, 4.22, 4.22, 4.22	7.10, 7.10, 7.10, 7.10	9.00, 9.00, 9.00, 9.00
FO	0.70, 0.70, 0.70, 0.70	1.00, 1.00, 1.00, 1.00	1.63, 1.63, 1.63, 1.63	1.29, 1.29, 1.29, 1.29	1.32, 1.32, 1.32, 1.32	2.12, 2.12, 2.12, 2.12	2.69, 2.69, 2.69, 2.69	1.61, 1.61, 1.61, 1.61	2.68, 2.68, 2.68, 2.68	3.14, 3.14, 3.14, 3.14	2.96, 2.96, 2.96, 2.96	4.98, 4.98, 4.98, 4.98	6.32, 6.32, 6.32, 6.32
MH	0.43, 0.43, 0.43, 0.43	0.61, 0.61, 0.61, 0.61	1.00, 1.00, 1.00, 1.00	0.79, 0.79, 0.79, 0.79	0.81, 0.81, 0.81, 0.81	1.30, 1.30, 1.30, 1.30	1.65, 1.65, 1.65, 1.65	0.99, 0.99, 0.99, 0.99	1.64, 1.64, 1.64, 1.64	1.93, 1.93, 1.93, 1.93	1.82, 1.82, 1.82, 1.82	3.06, 3.06, 3.06, 3.06	3.88, 3.88, 3.88, 3.88
EQ	0.54, 0.54, 0.54, 0.54	0.77, 0.77, 0.77, 0.77	1.26, 1.26, 1.26, 1.26	1.00, 1.00, 1.00, 1.00	1.02, 1.02, 1.02, 1.02	1.64, 1.64, 1.64, 1.64	2.08, 2.08, 2.08, 2.08	1.25, 1.25, 1.25, 1.25	2.07, 2.07, 2.07, 2.07	2.43, 2.43, 2.43, 2.43	2.29, 2.29, 2.29, 2.29	3.85, 3.85, 3.85, 3.85	4.89, 4.89, 4.89, 4.89
EL	0.53, 0.53, 0.53, 0.53	0.76, 0.76, 0.76, 0.76	1.24, 1.24, 1.24, 1.24	0.98, 0.98, 0.98, 0.98	1.00, 1.00, 1.00, 1.00	1.61, 1.61, 1.61, 1.61	2.05, 2.05, 2.05, 2.05	1.23, 1.23, 1.23, 1.23	2.03, 2.03, 2.03, 2.03	2.38, 2.38, 2.38, 2.38	2.25, 2.25, 2.25, 2.25	3.78, 3.78, 3.78, 3.78	4.79, 4.79, 4.79, 4.79
ST	0.33, 0.33, 0.33, 0.33	0.47, 0.47, 0.47, 0.47	0.77, 0.77, 0.77, 0.77	0.61, 0.61, 0.61, 0.61	0.62, 0.62, 0.62, 0.62	1.00, 1.00, 1.00, 1.00	1.27, 1.27, 1.27, 1.27	0.76, 0.76, 0.76, 0.76	1.27, 1.27, 1.27, 1.27	1.48, 1.48, 1.48, 1.48	1.40, 1.40, 1.40, 1.40	2.35, 2.35, 2.35, 2.35	2.98, 2.98, 2.98, 2.98
TH	0.26, 0.26, 0.26, 0.26	0.37, 0.37, 0.37, 0.37	0.60, 0.60, 0.60, 0.60	0.48, 0.48, 0.48, 0.48	0.49, 0.49, 0.49, 0.49	0.79, 0.79, 0.79, 0.79	1.00, 1.00, 1.00, 1.00	0.60, 0.60, 0.60, 0.60	0.99, 0.99, 0.99, 0.99	1.16, 1.16, 1.16, 1.16	1.10, 1.10, 1.10, 1.10	1.85, 1.85, 1.85, 1.85	2.34, 2.34, 2.34, 2.34

Table 7-20: (Continued)

	FH	FO	MH	EQ	EL	ST	TH	FE	ES	CO	EH	CS	NV
FE	0.43, 0.43, 0.43, 0.43	0.62, 0.62, 0.62, 0.62	1.01, 1.01, 1.01, 1.01	0.80, 0.80, 0.80, 0.80	0.82, 0.82, 0.82, 0.82	1.31, 1.31, 1.31, 1.31	1.67, 1.67, 1.67, 1.67	1.00, 1.00, 1.00, 1.00	1.66, 1.66, 1.66, 1.66	1.94, 1.94, 1.94, 1.94	1.84, 1.84, 1.84, 1.84	3.09, 3.09, 3.09, 3.09	3.91, 3.91, 3.91, 3.91
ES	0.26, 0.26, 0.26, 0.26	0.37, 0.37, 0.37, 0.37	0.61, 0.61, 0.61, 0.61	0.48, 0.48, 0.48, 0.48	0.49, 0.49, 0.49, 0.49	0.79, 0.79, 0.79, 0.79	1.01, 1.01, 1.01, 1.01	0.60, 0.60, 0.60, 0.60	1.00, 1.00, 1.00, 1.00	1.17, 1.17, 1.17, 1.17	1.11, 1.11, 1.11, 1.11	1.86, 1.86, 1.86, 1.86	2.36, 2.36, 2.36, 2.36
CO	0.22, 0.22, 0.22, 0.22	0.32, 0.32, 0.32, 0.32	0.52, 0.52, 0.52, 0.52	0.41, 0.41, 0.41, 0.41	0.42, 0.42, 0.42, 0.42	0.67, 0.67, 0.67, 0.67	0.86, 0.86, 0.86, 0.86	0.51, 0.51, 0.51, 0.51	0.85, 0.85, 0.85, 0.85	1.00, 1.00, 1.00, 1.00	0.94, 0.94, 0.94, 0.94	1.59, 1.59, 1.59, 1.59	2.10, 2.10, 2.10, 2.01
EH	0.24, 0.24, 0.24, 0.24	0.34, 0.34, 0.34, 0.34	0.55, 0.55, 0.55, 0.55	0.44, 0.44, 0.44, 0.44	0.44, 0.44, 0.44, 0.44	0.71, 0.71, 0.71, 0.71	0.91, 0.91, 0.91, 0.91	0.54, 0.54, 0.54, 0.54	0.90, 0.90, 0.90, 0.90	1.06, 1.06, 1.06, 1.06	1.00, 1.00, 1.00, 1.00	1.68, 1.68, 1.68, 1.68	2.13, 2.13, 2.13, 2.13
ES	0.14, 0.14, 0.14, 0.14	0.20, 0.20, 0.20, 0.20	0.33, 0.33, 0.33, 0.33	0.26, 0.26, 0.26, 0.26	0.26, 0.26, 0.26, 0.26	0.42, 0.42, 0.42, 0.42	0.54, 0.54, 0.54, 0.54	0.32, 0.32, 0.32, 0.32	0.54, 0.54, 0.54, 0.54	0.63, 0.63, 0.63, 0.63	0.60, 0.60, 0.60, 0.60	1.00, 1.00, 1.00, 1.00	1.27, 1.27, 1.27, 1.27
NV	0.11, 0.11, 0.11, 0.11	0.16, 0.16, 0.16, 0.16	0.26, 0.26, 0.26, 0.26	0.20, 0.20, 0.20, 0.20	0.21, 0.21, 0.21, 0.21	0.34, 0.34, 0.34, 0.34	0.43, 0.43, 0.43, 0.43	0.26, 0.26, 0.26, 0.26	0.42, 0.42, 0.42, 0.42	0.50, 0.50, 0.50, 0.50	0.47, 0.47, 0.47, 0.47	0.79, 0.79, 0.79, 0.79	1.00, 1.00, 1.00, 1.00

Table 7-21: Safety risk magnitude of hazard groups in building construction project 2

System	Hazard groups	Hazard group scores	Weight factors	Hazard group categories
Building construction project 2 (2.40, Average: 100%)	Falls from height	2.25	0.192	Average: 100%
	Falling objects	2.32	0.134	Average: 100%
	Manual handling	2.10	0.082	Average: 100%
	Equipment, machinery and tools	2.15	0.104	Average: 100%
	Electricity	2.50	0.102	Average: 100%
	Slips and trips	2.50	0.063	Average: 100%
	Traffic hazards	3.00	0.050	Average: 100%
	Fire and explosions	3.00	0.083	Average: 100%
	Exposure to hazardous substances	2.50	0.050	Average: 100%
	Collapse of site structure	2.10	0.042	Average: 100%
	Confined space	2.25	0.045	Average: 100%
	Ergonomic/ Human factors	3.00	0.027	Average: 100%
	Noise and vibration	2.15	0.021	Average: 100%

After the weight factors were calculated by using the MFAHP, the FTOPSIS method was used to obtain the final ranking for evaluating of important safety risks. The results of the calculation of the CC_i^* index of all 13 hazard groups are presented in Table 7-22.

7.3.6 Safety Risk Controls and Discussions

The results of the proposed model obtained from this research are shown in Table 7-22. It can be ascertained that among the 13 hazard groups, FH, FO, FE and EQ are higher-ranking hazard groups than any others and need the most attention. Conversely, CO and NV are lower –ranking hazard groups. The 13 hazard groups in Table 7-22, are presented in Figure 7-11.

Table 7-22: Calculation of fuzzy closeness coefficient for each hazard group in building construction project 2

Hazard groups	Normalised Fuzzy	Weighted Normalised	*d+*	*d-*	CC_i^*	*Rank*
FH	0.926, 0.926, 1.000, 1.000	0.178, 0.178, 0.192, 0.192	0.0000	0.3480	1.0000	1
FO	0.797, 0.869, 0.911, 0.986	0.107, 0.117, 0.123, 0.133	0.1301	0.2188	0.6271	2
MH	0.353, 0.353, 0.353, 0.353	0.029, 0.029, 0.029, 0.029	0.3117	0.0364	0.1046	8
EQ	0.579, 0.579, 0.676, 0.676	0.060, 0.060, 0.070, 0.070	0.2389	0.1093	0.3140	4
EL	0.482, 0.482, 0.482, 0.482	0.049, 0.049, 0.049, 0.049	0.2715	0.0766	0.2200	5
ST	0.665, 0.665, 0.665, 0.665	0.042, 0.042, 0.042, 0.042	0.2853	0.0628	0.1803	6
TH	0.554, 0.554, 0.554, 0.554	0.028, 0.028, 0.028, 0.028	0.3146	0.0335	0.0962	9
FE	0.900, 0.900, 0.990, 0.990	0.075, 0.075, 0.083, 0.083	0.2121	0.1359	0.3906	3
ES	0.756, 0.756, 0.756, 0.756	0.038, 0.038, 0.038, 0.038	0.2940	0.0541	0.1554	7
CO	0.292, 0.292, 0.331, 0.331	0.013, 0.013, 0.014, 0.014	0.3432	0.0051	0.0147	12
EH	0.360, 0.384, 0.408, 0.432	0.016, 0.017, 0.019, 0.020	0.3339	0.0142	0.0409	11
CS	0.798, 0.798, 0.878, 0.878	0.022, 0.022, 0.024, 0.024	0.3246	0.0235	0.0674	10
NV	0.513, 0.513, 0.513, 0.513	0.011, 0.011, 0.011, 0.011	0.3480	0.0000	0.0000	13

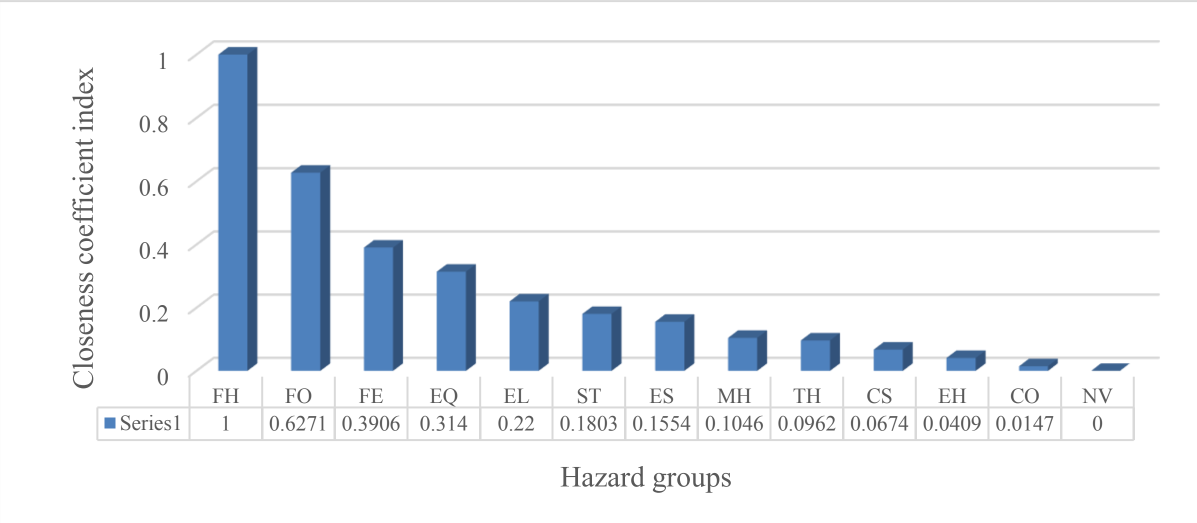


Figure 7-11: Ranking of all hazard groups in building construction project 2 to CC_i^* index

Recommended measures for each hazard group with the most important safety risk are presented and discussed below.

Falls from height has nine hazardous events: working platform, erection of scaffolding, climbing cranes, temporary ladder, hole in the ground, working on height unprotected, through opening elevator shaft, working formwork, and excavation hole. To reduce the probability of occurrence and severity of consequence, an induction safety training course on using fall protection devices and safety harnesses and safety belts should be provided. Furthermore, guard rails and toe boards should be provided for heights over 2 metres (including gates and pilling frames safety harnesses should be used, ladders should be inspected daily for defects, and mobile access tower cranes should be required if possible. Furthermore, warning notices should be displayed on work sites to remind workers to follow the SSOP.

Falling objects has five hazardous events: part of climbing cranes, scaffolds; operating, cleaning and clearing; hand-held tools; post-tension; and blown by wind. To mitigate the probability and severity of consequence, proper lifting and rigging methods should be adopted and suitable training on safe use of lifting appliances and lifting gear should be provided for operators and workers, including suitable training on safe stacking and rigging of materials. Furthermore, warning notices should be displayed to remind other workers entering the affected areas. Moreover, the wearing of safety helmets on site should be enforced and the chin strip straps for the safety helmet should be used. Lifting gear should be visually inspected to ensure that it is in good condition and safe to use.

Fire and explosion has four hazardous events: hot work, working near flammables, gas cylinder or hose leakage, and fire extinguisher has been discharged. Therefore, fire prevention training should be provided for workers and they should keep the working areas clean and tidy. Training on safe use of electricity and welding machine should also be provided. Furthermore, a competent electrician should be appointed to check the electrical appliances and welding regularly, and smoking should be prohibited during the welding operation. “No smoking” signs should be displayed in the affected areas and a hot work permit system should be implemented. Moreover, a sufficient numbers of dry powder type fire extinguishers need to be provided near the welding operation areas and fire precaution training to welders/hot work operators is required.

Controlling and monitoring should be applied in the confined space and noise and vibration groups. Although these hazard groups have been identified as minor safety risks for building construction project 2, the control measures should still be maintained effectively. For example, for the confined space hazard group, there should be a supervisor or watcher with a lifeline when a person is entering a confined space, and all channels, drains and catch pits should be inspected and maintained.

The results of the proposed construction safety risk assessment model were compared with the method developed by building construction project 2, as illustrated in Table 7-23. The safety risk ranking from the developed construction safety risk assessment model is slightly different from the method developed by building construction project 2. For instance, in the proposed, falls from height (hole in the ground, working on height unprotected, and through opening elevator shaft) had a safety risk score of 3.00 and were in the Average category with confidence of 100 per cent, whereas in building construction project 2's method it had a safety risk levels of moderate. Those hazardous events are in a similar position in both methods; however, building construction project 2's method cannot provide more safety risk information to the safety management team for the purposes of decision making. Therefore, it should be noted that the proposed construction safety risk management model can provide safety risk information and produce safety risk ranking similar to risk level estimated by building construction project 2's method.

Table 7-23: Safety risk level of building construction project 2

Proposed Construction Safety Risk Management Method			Building Construction Project 2's Method
Hazardous events	Safety risk score	Safety risk categories	Risk level
FH-05 Hole in the ground	3.00	Average:100%	Moderate
FH-06 Working on height unprotected	3.00	Average:100%	Moderate
FH-07 Through opening elevator shaft	3.00	Average:100%	Moderate
FO-11 Operating, cleaning and clearing	3.00	Average:100%	Moderate
FO-14 Blown by wind	3.00	Average:100%	Moderate
EL-26 Arc welding machine	3.00	Average:100%	Moderate
ST-29 Trips caused by small change in level	3.00	Average:100%	Moderate
ST-30 Trips caused by water pipes	3.00	Average:100%	Moderate
TH-31 Collison with another vehicle	3.00	Average:100%	Moderate
TH-32 Collision with plant/people	3.00	Average:100%	Moderate
FE-33 Hot work	3.00	Average:100%	Moderate
FE-34 Working near flammables	3.00	Average:100%	Moderate
FE-35 Gas cylinder or hose leakage	3.00	Average:100%	Moderate
FE-36 Fire extinguisher has been discharged	3.00	Average:100%	Moderate
ES-37 Cement dust	3.00	Average:100%	Moderate
CS-43 Deep excavations	3.00	Average:100%	Moderate
EH-45 Poor work posture	3.00	Average:100%	Moderate
EH-46 Extreme muscular exertion	3.00	Average:100%	Moderate
FO-12 Hand-held tools	2.71	Average:100%	Moderate
FH-09 Excavation hole	2.64	Average:100%	Moderate
FO-13 Post-tension	2.64	Average:100%	Moderate
EQ-21 Welding machine	2.64	Average:100%	Moderate
EQ-22 Concrete breaking machine	2.64	Average:100%	Moderate
EL-23 Wires, switchboards	2.64	Average:100%	Moderate
ST-27 Tripping over building materials	2.64	Average:100%	Moderate

Table 7-23: (Continued)

Proposed Construction Safety Risk Management Method			Building Construction Project 2's Method
Hazardous events	Safety risk score	Safety risk categories	Risk level
NV-52 Concrete pump machine	2.64	Average:100%	Moderate
FO-10 Part of climbing cranes, scaffolds	2.26	Average:100%	Moderate
FH-03 Climbing cranes	2.25	Average:100%	Moderate
MH-16 Poor rigging	2.25	Average:100%	Moderate
EQ-20 Grinder machine	2.25	Average:100%	Moderate
EL-24 Electrical work	2.25	Average:100%	Moderate
ST-28 Slipping on wet surfaces	2.25	Average:100%	Moderate
CO-40 Collapse of scaffolding	2.25	Average:100%	Moderate
CO-39 Temporary structure	2.10	Average:100%	Moderate
CO-41 Steel sheet piles	2.10	Average:100%	Moderate
CO-42 Kingpost	2.10	Average:100%	Moderate
ES-38 Formwork striking oil, epoxy	2.01	Average:100%	Minor
FH-01 Working platform	2.00	Average:100%	Moderate
CS-44 Closed tanks	2.00	Average:100%	Minor
FH-04 Temporary ladder	1.89	Acceptable:22%, Average:78 %	Minor
MH-15 Hoists	1.89	Acceptable:22%, Average:78 %	Minor
MH-17 Mobile crane lifting	1.89	Acceptable:22%, Average:78 %	Minor
FH-02 Erection of scaffolding	1.50	Acceptable:100%	Minor
FH-08 Working formwork	1.50	Acceptable:100%	Minor
EQ-18 Cutting machine	1.50	Acceptable:100%	Minor
EQ-19 Steel bar bending machine	1.50	Acceptable:100%	Minor
EL-25 Overhead power lines	1.50	Acceptable:100%	Minor
NV-47 Piling	1.50	Acceptable:100%	Minor
NV-48 Excavation	1.50	Acceptable:100%	Minor
NV-49 Hammering	1.50	Acceptable:100%	Minor
NV-50 Vibrator machine	1.50	Acceptable:100%	Minor
NV-51 Hand-held power tools	1.50	Acceptable:100%	Minor

7.4 Case Study 3: Building Construction Project

7.4.1 Background of Case Study 3

"Building Construction Company 3" is used instead of the building construction company's name due to business confidentiality. This construction project is a condominium project in Bangkok, Thailand. The condominium comprises two buildings with 34 floors and 864 units.

7.4.2 Establishing a Safety Risk Management Team

Five experts involved in the safety risk management model were selected based on their individual skills, knowledge, experience, and expertise. One expert is a project manager who has worked on building construction project for more than 10 years. One expert is a site manager with 25 years' experience and one is a project co-ordinator with 10 years' experience of working on building construction projects. The other experts are safety officers, as shown in Table 7-24

Table 7-24: Description of experts' contribution factors

Expert	Title of expert	Score	Years of experience	Score	Weighting score	Weighting factor
Expert 1	Project Manager	5	10	4	10	0.25
Expert 2	Site Manager	4	25	5	10	0.25
Expert 3	Project Co-ordinator	4	10	4	10	0.22
Expert 4	Safety Officer	2	9	3	5	0.14
Expert 5	Safety Officer	2	8	3	5	0.14

7.4.3 Safety Hazard Identification

To carry out safety risk assessment and management, following brainstorming and discussions with safety risk management team of building construction project 3 information was gathered and verified to ensure that it contained all the hazard groups and hazardous events. The building construction safety system is divided into 13 hazard groups: falls from height; falling objects; manual handling; equipment machinery and tools; electricity; slips and trips; traffic hazards; fire and explosions; exposure to hazardous substances, collapse of site structure, confined space, ergonomic/human factors and noise and vibration. Each hazard group includes several identified safety risk events and is described below.

(1) *Falls from height* includes seven hazardous events: working platform (FH-0001), erection of scaffolding (FH-0002,) climbing cranes (FH-0003), temporary ladder (FH-0004), hole in the ground (FH-0005), working on height unprotected (FH-0006), and through opening elevator shaft (FH-0007).

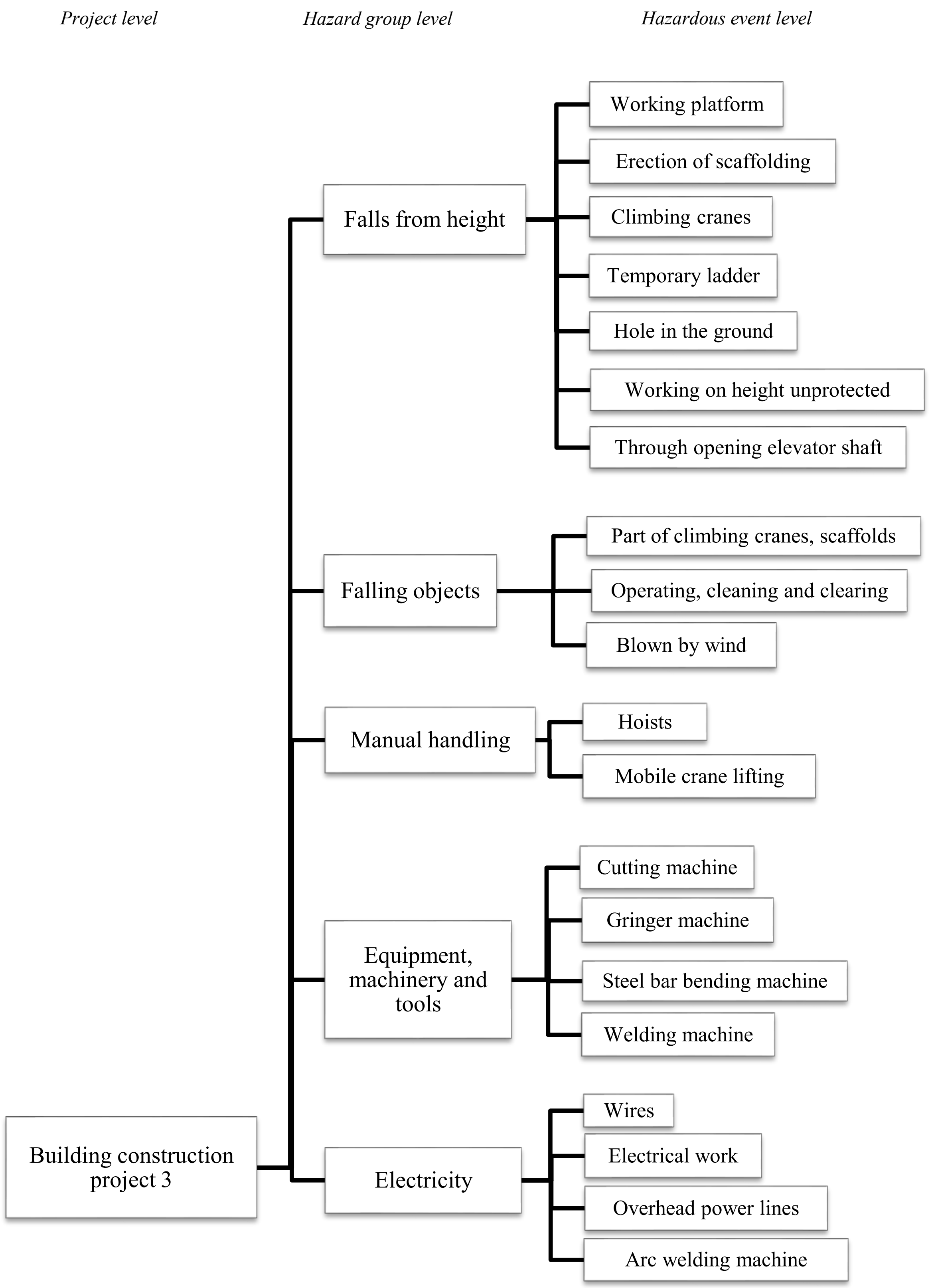
(2) *Falling objects* includes three hazardous events: part of climbing cranes, scaffolds (FO-0008), operating, cleaning and clearing (FO-0009) and blown by wind (FO-0010).

(3) *Manual handling* includes two hazardous events: hoists (MH-0011) and mobile crane lifting (MH-0012).

(4) *Equipment machinery and tools* includes four hazardous events: cutting machine (EQ-0013), steel bar bending machine (EQ-0014), grinder machine (EQ-0015) and welding machine (EQ-0016).

(5) *Electricity* includes four hazardous events: wires (EL-0017), electrical work (EL-0018), overhead power lines (EL-0019) and arc welding machine (EL-0020).

(6) *Slips and trips* includes four hazardous events: tripping over building materials (ST-0021), slipping on wet surfaces (ST-0022), trips caused by small change in level (ST-0023) and trips caused by water pipes, rebar (ST-0024).


Project level
Hazard group level
Hazardous event level
Working platform
Erection of scaffolding
Falls from height
Climbing cranes
Temporary ladder
Hole in the ground
Working on height unprotected
Through opening elevator shaft
Part of climbing cranes, scaffolds
Falling objects
Operating, cleaning and clearing
Blown by wind
Hoists
Manual handling
Mobile crane lifting
Cutting machine
Gringer machine
Equipment, machinery and tools
Steel bar bending machine
Welding machine
Wires
Electrical work
Building construction project 3
Electricity
Overhead power lines
Arc welding machine

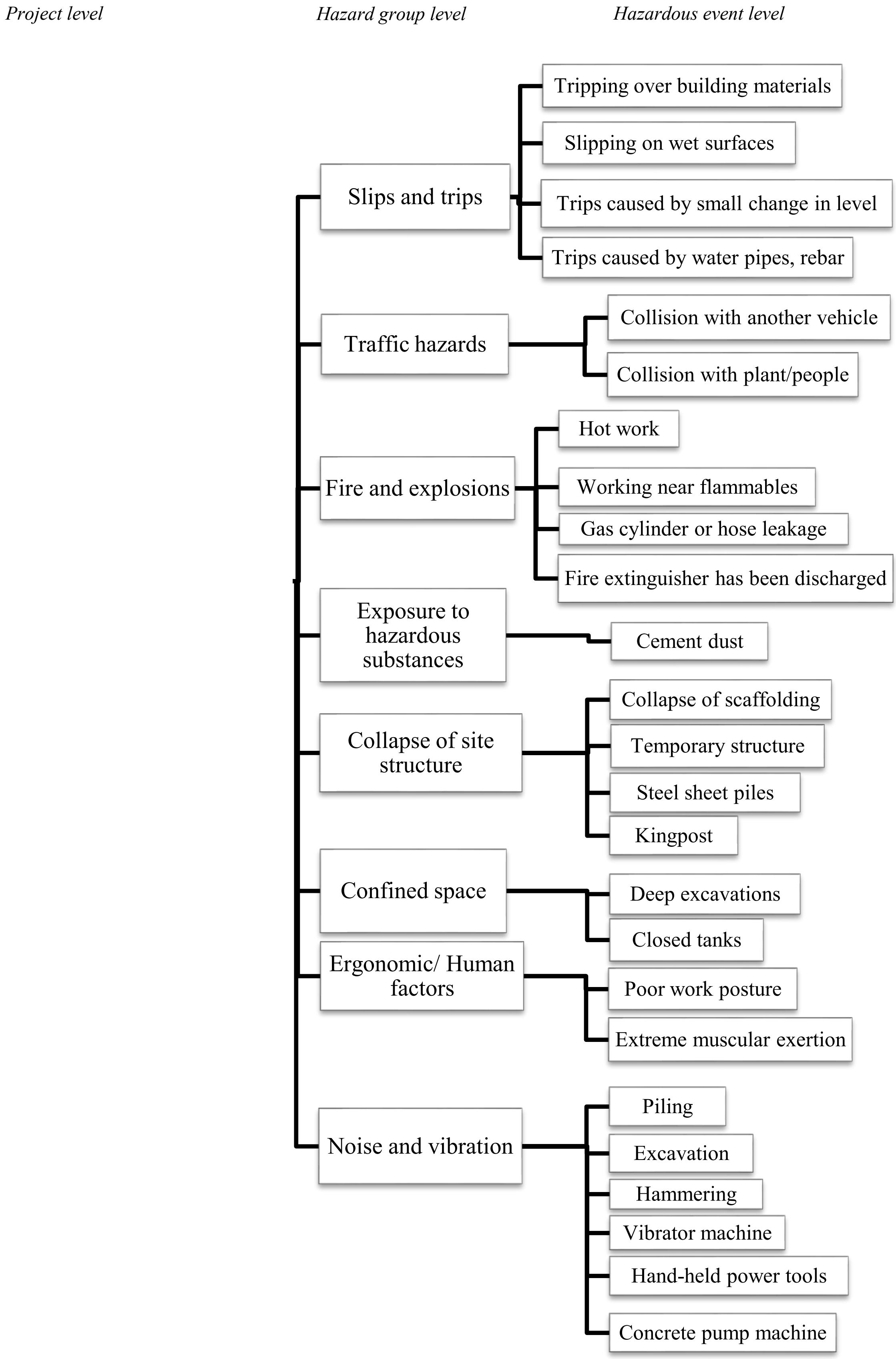


Figure 7-12: Hazard identification at building construction project 3

(7) *Traffic hazards* includes two hazardous events: collision with another vehicle (TH-0025) and collision with plant/people (TH-0026).

(8) *Fire and explosions* includes four hazardous events: hot work (FE-0027), working near flammables (FE-0028), gas cylinder or hose leakage (FE-0029) and fire extinguisher has been discharged (FE-0030).

(9) *Exposure to hazardous substances* includes one hazardous event: cement dust (ES-0031).

(10) *Collapse of site structure* includes four hazardous events: collapse of boom (cranes) (CO-0032), collapse of scaffolding (CO-0033), steel sheet piles (CO-0034) and kingpost (CO-0035).

(11) *Confined space* includes two hazardous events: deep excavations (CS-0036) and closed tanks (CS-0037).

(12) *Ergonomic and human factors* include two hazardous events: poor work posture (EH-0038) and extreme muscular exertion (EH-0039).

(13) *Noise and vibration* include six hazardous events: piling (NV-0040), excavation (NV-0041), hammering (NV-0042), vibrator machine (NV-0043), hand-held power tools (NV-0044) and concrete pump machine (NV-0045).

7.4.4 Safety Risk Estimation

As the safety risk management process of building construction project 3 is similar to the case study of safety risk management of building construction projects 1 and 2, the linguistic variables of the risk parameters, PC, PO and SC and the fuzzy rule base were employed in this case. Once the safety risk criteria were established and the data on PO, SC and PC were calculated using fuzzification, fuzzy aggregation, fuzzy inference, and defuzzification, the safety risk magnitude of all the hazardous events of building construction project 3 were obtained as shown in Table 7-25.

To assess the overall safety risk magnitude of project 3, the weights of hazard groups were estimated by using MFAHP based on trapezoidal fuzzy number. Consequently, the overall safety risk magnitude of building construction project 3 is 3.36 and the safety risk is between *Average* and *High* with confidence of 28 per cent for *Average* and 72 per cent for *High* as shown in Table 7-26.

Table 7-25: Safety risk magnitude of building construction project 3

Hazard groups	Hazardous events	Aggregated STFN Probability of occurrence	Aggregated STFN Severity of consequence	Aggregated STFN Probability of consequence	Safety risk scores	Safety risk categories
Falls from height	FH-0001 Working platform	2.75, 2.89, 3.67, 3.81	2.94, 3.22, 4.08, 4.36	2.86, 3.00, 3.14, 3.28	3.32	Average: 36%, High: 64%
	FH-0002 Erection of scaffolding	2.83, 3.25, 3.50, 3.78	2.61, 2.75. 3.50, 3.78	2.64, 2.78, 2.92, 3.06	3.09	Average: 82%, High: 18%
	FH-0003 Climbing cranes	3.33, 3.61, 4.22, 4.50	3.80, 3.94, 4.22, 4.36	2.89, 3.03, 3.17, 3.31	3.77	High: 100%
	FH-0004 Temporary ladder	3.11, 3.11, 3.64, 3.64	2.72, 3.00, 3.22, 3.50	2.42, 2.56, 2.92, 3.06	3.09	Average: 82%, High: 18%
	FH-0005 Hole in the ground	3.36, 3.50, 4.11, 4.25	3.80, 3.94, 4.72, 5.00	3.31, 3.45, 3.92, 4.06	4.05	High: 90%, Unacceptable: 10%
	FH-0006 Working on height unprotected	4.00, 4.00, 4.50, 4.50	2.72, 3.00, 4.11, 4.39	3.39, 3.53, 3.92, 4.06	3.80	High: 100%
	FH-0007 Through opening elevator shaft	3.33, 3.61, 3.75, 4.03	4.44, 4.58, 4.86, 5.00	2.81, 2.95, 3.70, 3.84	3.86	High: 100%
Falling objects	FO-0008 Part of climbing cranes, scaffolds	3.00, 3.14, 3.28, 3.42	3.22, 3.50, 4.11, 4.39	2.92, 3.06, 3.78, 3.92	3.46	Average: 8%, High: 92%
	FO-0009 Operating, cleaning and clearing	2.78, 3.06, 3.53, 3.81	2.50, 2.64, 3.00, 3.14	2.42, 2.56, 3.06, 3.20	3.18	Average: 64%, High: 36%
	FO-0010 Blown by wind	3.19, 3.47, 3.86, 4.14	2.11, 2.39, 2.61, 2.89	2.92, 2.92, 3.45, 3.45	3.15	Average: 70%, High: 30%
Manual handling	MH-0011 Hoists	2.83, 3.11, 3.36, 3.64	2.72, 2.86, 3.14, 3.28	3.06, 3.20, 3.34, 3.48	3.35	Average: 30%, High: 70%
	MH-0012 Mobile crane lifting	3.33, 3.61, 4.00, 4.28	3.30, 3.58, 3.94, 4.22	2.67, 2.81,3.09, 3.23	3.56	High: 100%
Equipment, machinery and tools	EQ-0013 Cutting machine	3.44, 3.58, 4.22, 4.36	2.44, 2.72, 3.22, 3.50	2.56, 2.56, 2.84' 2.84	3.36	Average: 76%, High: 24%
	EQ-0014 Steel bar bending machine	2.28, 2.42, 3.28, 3.42	2.44, 2.72, 2.97, 3.25	2.17, 2.31, 2.70, 2.84	3.00	Average: 100%
	EQ-0015 Grinder machine	2.36, 2.64, 3.36, 3.64	2.52, 2.80, 3.19, 3.47	2.56, 2.70, 3.31, 3.45	3.38	Average: 24%, High: 76%
	EQ-0016 Welding machine	2.28, 2.42, 3.28, 3.42	2.55, 2.83, 2.83, 3.11	2.42, 2.56, 3.20, 3.34	3.12	Average: 76%, High: 24%
Electricity	EL-0017 Wires	2.61, 2.89, 3.50, 3.78	3.02, 3.30, 3.94, 4.22	2.78, 2.92, 3.06, 3.20	3.24	Average: 52%, High: 48%
	EL-0018 Electrical work	2.72, 3.00, 3.47, 3.75	2.86, 3.14, 3.75, 4.03	2.67, 2.81, 2.95, 3.09	3.12	Average: 76%, High: 24%
	EL-0019 Overhead power lines	2.44, 2.72, 2.97, 3.25	2.69, 2.97, 3.22, 3.50	2.28, 2.42, 3.03, 3.17	3.21	Average: 58%, High: 42%
	EL-0020 Arc welding machine	2.36, 2.64, 3.14, 3.42	2.94, 3.22, 3.22, 3.50	2.14, 2.42, 2.89, 3.17	3.23	Average: 54%, High: 46%
Slips and trips	ST-0021 Tripping over building materials	2.36, 2.64, 3.14, 3.42	2.22, 2.36, 2.86, 3.00	2.75, 2.89, 3.28, 3.42	3.00	Average: 100%
	ST-0022 Slipping on wet surfaces	2.75, 2.89, 3.53, 3.67	2.08, 2.36, 2.58, 2.86	2.61, 2.89, 2.89, 3.17	3.00	Average: 100%
	ST-0023 Trips caused by small change level	2.22, 2.36, 3.00, 3.14	1.61, 1.61, 2.36, 2.36	2.50, 2.64, 3.03, 3.17	2.34	Average: 100%
	ST-0024 Trips caused by water pipes	2.25, 2.39, 3.25, 3.39	2.22, 2.50, 3.00, 3.28	2.53, 2.81, 3.28, 3.56	3.26	Average: 48%, High: 52%
Traffic hazards	TH-0025 Collision with another vehicle	2.00, 2.14, 2.75, 2.89	2.39, 2.53, 3.14, 3.28	1.89, 1.89, 2.17, 2.17	2.34	Average: 100%
	TH-0026 Collision with plant/people	2.00, 2.14, 2.75, 2.89	2.50, 2.78, 3.25, 3.53	2.03, 2.17, 2.56, 2.70	3.00	Average: 100%

Hazard Groups	Hazardous Events	Aggregated STFN Probability of occurrence	Aggregated STFN Severity of consequence	Aggregated STFN Probability of consequence	Safety risk scores	Safety Risk categories
Fire and explosions	FE-0027 Hot work	2.72, 2.86, 3.72, 3.86	2.69, 2.69, 3.19, 3.19	2.64, 2.78, 3.17, 3.31	3.28	Average: 44%, High: 56%
	FE-0028 Working near flammables	2.53, 2.67, 3.03, 3.17	2.58, 2.72, 3.22, 3.50	2.42, 2.70, 2.95, 3.23	3.21	Average: 58%, High: 42%
	FE-0029 Gas cylinder or hose leakage	2.03, 2.17, 2.67, 2.81	2.97, 3.11, 3.72, 3.86	2.28, 2.56, 2.81, 3.09	3.00	Average: 100%
	FE-0030 Fire extinguisher has been discharged	2.50, 2.64, 3.00, 3.14	2.94, 3.22, 3.83, 4.11	2.17, 2.45, 2.70, 2.98	3.12	Average: 76%, High: 24%
Exposure to hazardous substances	ES-0031 Cement dust	3.00, 3.14, 3.53, 3.67	2.22, 2.36, 2.97, 3.11	3.00, 3.28, 3.53, 3.81	3.46	Average: 8%, High: 92%
Collapse of site structures	CO-0032 Temporary structure	1.89, 2.03, 2.64, 2.78	3.80, 3.94, 4.47, 4.75	2.34, 2.34, 3.12, 3.12	3.19	Average: 62%, High: 38%
	CO-0033 Collapse of scaffolding	2.36, 2.50, 2.89, 3.03	3.72, 3.86, 4.61, 4.75	2.34, 2.34, 3.59, 3.59	3.50	High: 100%
	CO-0034 Steel sheet piles	2.25, 2.53, 3.25, 3.53	2.47, 2.75, 3.61, 3.89	2.20, 2.20, 3.06, 3.06	3.11	Average: 78%, High: 22%
	CO-0035 Kingpost	1.72, 2.00, 2.50, 2.78	2.97, 3.25, 4.11, 4.39	1.95, 1.95, 2.73, 2.73	2.39	Average: 100%
Confined space	CS-0036 Deep excavations	2.25, 2.39, 3.03, 3.17	3.08, 3.22, 3.75, 4.03	2.20, 2.20, 3.20, 3.20	3.04	Average: 92%, High: 8%
	CS-0037 Closed tanks	2.03, 2.17, 3.03, 3.17	2.83, 2.97, 3.97, 4.25	2.06, 2.06, 3.31, 3.31	3.21	Average: 58%, High: 42%
Ergonomic / Human factors	EH-0038 Poor work posture	2.14, 2.42, 2.89, 3.17	2.25, 2.25, 3.00, 3.00	2.42, 2.70, 2.70, 2.98	3.00	Average: 100%
	EH-0039 Extreme muscular exertion	2.28, 2.42, 3.03, 3.17	2.61, 3.25, 3.39, 3.78	3.17, 3.70, 3.95, 4.48	3.34	Average: 32%, High: 68%
Noise and vibration	NV-0040 Piling	3.03, 3.03, 3.56, 3.56	2.61, 2.61, 3.14, 3.14	3.17, 3.31, 3.92, 4.06	3.22	Average: 56%, High: 44%
	NV-0041 Excavation	3.03, 3.17, 3.53, 3.67	2.72, 2.86, 3.72, 3.86	2.67, 2.95, 3.42, 3.70	3.47	Average: 6%, High: 94%
	NV-0042 Hammering	3.28, 3.42, 3.56, 3.70	2.47, 2.47, 3.72, 3.72	2.78, 3.06, 3.31, 3.59	3.50	High: 100%
	NV-0043 Vibrator machine	2.53, 2.81, 2.81, 3.09	2.11, 2.25, 2.64, 2.78	2.67, 2.95, 3.20, 3.48	3.00	Acceptable: 100%
	NV-0044 Hand-held power tools	3.03, 3.17, 3.67, 3.81	2.58, 2.72, 3.11, 3.25	3.00, 3.28, 3.78, 4.06	3.38	Average: 24%, High: 76%
	NV-0045 Concrete pump machine	2.28, 2.42, 3.03, 3.17	1.61, 1.61, 2.61, 2.61	3.06, 3.31, 3.59, 3.84	2.45	Average: 100%

Table 7-26: Safety risk magnitude of hazard group in building construction project 3

System	Hazard groups	Hazard group scores	Weight factors	Hazard group categories
Building construction project 3 (3.36, Average: 28% and High: 72%)	Falls from height	3.80	0.185	High: 100%
	Falling objects	3.40	0.147	Average: 20%, High: 80%
	Manual handling	3.57	0.101	High: 100%
	Equipment, machinery and tools	3.38	0.112	Average: 24%, High: 76%
	Electricity	3.24	0.094	Average: 52%, High: 48%
	Slips and trips	2.62	0.073	Average: 100%
	Traffic hazards	3.00	0.053	Average: 100%
	Fire and explosions	3.28	0.058	Average: 44%, High: 56%
	Exposure to hazardous substances	3.46	0.051	Average: 8%, High: 92%
	Collapse of site structure	2.99	0.043	Average: 100%
	Confined space	3.21	0.033	Average: 58%, High: 42%
	Ergonomic/Human factors	3.32	0.024	Average: 36%, High: 64%
	Noise and vibration	3.05	0.022	Average: 90%, High: 10%

7.4.5 Safety Risk Ranking

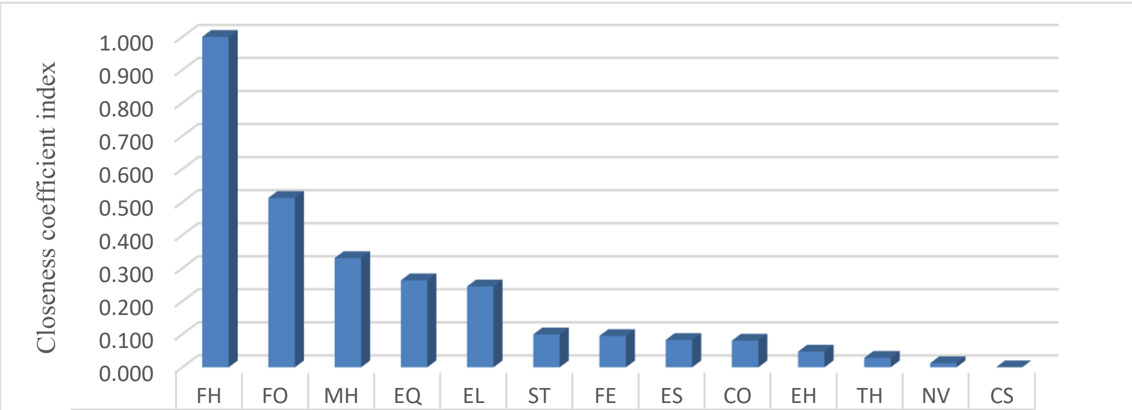
The weight factors were estimated by using the MFAHP and FTOPSIS methods to obtain the final ranking for evaluating important safety risks. The results of the calculation of the CC_i^* index of all 13 hazard groups are presented in Table 7-27.

Table 7-27: Calculation of fuzzy closeness coefficient for each hazard group in building construction project 3

Hazard groups	Normalised fuzzy	Weighted normalised	*d+*	*d-*	CC_i^*	*Rank*
FH	0.490, 0.551, 0.881, 1.000	0.091, 0.102, 0.163, 0.185	0.0000	0.2657	1.0000	1
FO	0.327, 0.390, 0.591, 0.682	0.048, 0.058, 0.087, 0.101	0.1295	0.1362	0.5126	2
MH	0.340, 0.421, 0.564, 0.676	0.034, 0.043, 0.057, 0.068	0.1781	0.0880	0.3306	3
EQ	0.249, 0.289, 0.447, 0.502	0.028, 0.032, 0.050, 0.056	0.1958	0.0699	0.2632	4
EL	0.254, 0.323, 0.489, 0.592	0.024, 0.030, 0.046, 0.056	0.2007	0.0651	0.2449	5
ST	0.167, 0.209, 0.341, 0.407	0.012, 0.015, 0.025, 0.030	0.2392	0.0265	0.0998	6
TH	0.118, 0.150, 0.265, 0.319	0.006, 0.008, 0.014, 0.017	0.2581	0.0076	0.0286	11
FE	0.224, 0.248, 0.436, 0.472	0.013, 0.014, 0.025, 0.027	0.2405	0.0252	0.0949	7
ES	0.232, 0.282, 0.429, 0.504	0.012, 0.014, 0.022, 0.026	0.2437	0.0220	0.0829	8
CO	0.238, 0.262, 0.554, 0.599	0.010, 0.011, 0.024, 0.026	0.2443	0.0215	0.0807	9
EH	0.219, 0.337, 0.470, 0.622	0.007, 0.011, 0.016, 0.021	0.2534	0.0127	0.0476	10
CS	0.177, 0.196, 0.421, 0.474	0.004, 0.005, 0.010, 0.012	0.2657	0.0000	0.0000	13
NV	0.272, 0.328, 0.500, 0.583	0.006, 0.007, 0.011, 0.013	0.2630	0.0033	0.0123	12

7.4.6 Safety Risk Controls and Discussions

The overall safety risk magnitude of building construction project 3 is 3.36 and is in the safety risk category of *Average* with confidence of 28 per cent and *High* with confidence of 72 per cent. Safety risk mitigations to reduce the overall safety risk magnitude are required. Thirteen identified hazard groups affected the overall safety risk magnitude in building construction project 3. It should be emphasised that the major contribution obtained from the results of the proposed model in Table 7-27 is that hazard groups FH, FO, MH, EQ and EL are high-ranking hazard groups and need the most attention. Conversely, hazard groups CS and NV are the lowest-ranking hazard groups. The ranking of the contributions of all 13 hazard groups in building construction project 3 in Table 7-27, is presented in Figure 7-13.



	FH	FO	MH	EQ	EL	ST	FE	ES	CO	EH	TH	NV	CS
Series1	1.000	0.513	0.331	0.263	0.245	0.100	0.095	0.083	0.081	0.048	0.029	0.012	0.000

Figure 7-13: Ranking of all hazard groups in building construction project 3 to CC_i^* index

Recommended measures for each hazard group with the most important safety risk are presented and discussed below.

Falls from height is one of the most important hazard groups in building construction projects. In this project, it has seven hazardous events: working platform, erection of scaffolding, climbing cranes, temporary ladder, hole in the ground, working on height unprotected, and through opening elevator shaft. Therefore, by reducing the safety risk magnitude of this hazard group, the probability of occurrence and the severity of consequence will be reduced significantly. For example, safety training and instruction should be provided for the workers, safety harnesses and safety belts should be provided, barricades should be erected, warning signs should be displayed and there should be supervision by safety personnel. Furthermore, gaps between scaffold boards should be minimised or eliminated and safe access to the workplaces should be maintained.

Falling from objects has three hazardous events: part of climbing cranes, scaffolds; operating, cleaning and clearing; and blown by wind. To reduce the safety risk magnitude of this hazard group, safety training on safe stacking and rigging of materials should be provided for workers, and lifting gears should be visually inspected before use to ensure that it is in good condition and safe to use. Furthermore, suitable training on safe use of lifting appliances and lifting gear should be provided for operators and workers. Moreover, warning notices should be displayed to remind other workers entering the affected areas, and wearing of safety helmets on site should be enforced.

The equipment, machinery and tools hazard group has four hazard events: cutting machine, steel bar bending machine, grinder machine, and welding machine. According to the statistics records of accidents, there are many different accidents and injuries involving use of machinery, such as a crush injury caused due to a missing or inadequate guard, and injuries caused by sharp edges or broken parts on equipment. Moreover, injuries are caused because of unsuitable work equipment, for instance, using the wrong tools for the job. Therefore, proper staff training is required to ensure that workers understand how to use and operate the work equipment safely, and maintain and inspect the work equipment properly. Finally, suitable protective equipment should be provided for workers using the work equipment, such as safety footwear, safety goggles, ear protectors, safety helmets, and protective gloves.

According to the results obtained from the proposed model, the cconfined space, noise and vibration, traffic hazards and ergonomic/human factors hazard groups pose a lower risk than the hazard groups mentioned above. Safety risk monitoring and controlling should be carried out to ensure that these hazard groups still have a plan and continually evaluate the plan's effectiveness in reducing safety risks. For example, there are two hazard events in the ergonomic/human factors hazard group: poor work posture and extreme muscular exertion. According to the statistics, accidents and injuries can involve workload and the working environment. Therefore, to control and monitor the safety risk magnitude of the ergonomic /human factors hazard group, tasks should be designed properly in accordance with ergonomic principles to take account of both human limitations and strengths. Furthermore, a manual handling risk assessment should be carried out by a competent person where appropriate, and instruction and monitoring by a competent supervisor should be provided.

The results of the proposed construction safety risk management model were not compared with the results from building construction project 3's method, as the safety risk assessment records of building construction project 3 are not available. However, the results of the proposed construction safety risk management model provide more safety risk information on both safety risk levels and categories of safety risk with a degree of confidence. The model can be used for decision-making purposes and can help the safety managers, project managers and engineers for mitigation and controlling all hazardous events and improve SSOP of construction project 3.

7.5 Case Study 4: Mass Rapid Transit Railway Construction Project

7.5.1 Background of Case Study 4

"Mass rapid transit railway construction company 4" is used instead of the mass rapid transit railway construction company's name due to business confidentiality. This construction project is a mass rapid transit (MRT) system project in Bangkok, Thailand. The MRT railway construction project comprises 17 stations and is 5.25 kilometres long.

7.5.2 Establishing a Safety Risk Management Team

Five experts involved in the safety risk management model were selected based on their individual skills, knowledge, experience, and expertise. One expert is a project supervisor who has worked on MRT railway construction projects for more than 38 years. One expert is a safety supervisor with 15 years' experience and another is a safety co-ordinator with 13 years' experience in working on railway construction project. The other two experts are site engineers, as shown in Table 7-28

Table 7-28: Description of experts' contribution factors

Expert	Title of expert	Score	Years of experience	Score	Weighting score	Weighting factor
Expert 1	Project Supervisor	3	38	5	8	0.25
Expert 2	Safety Supervisor	3	15	5	8	0.25
Expert 3	Safety Co-ordinator	3	13	4	7	0.22
Expert 4	Site Engineer	2	5	3	5	0.14
Expert 5	Site Engineer	2	3	2	4	0.14

7.5.3 Safety Hazard Identification

To carry out safety risk assessment and management, following discussions and brainstorming with the safety risk management team of MRT railway construction project 4, information was gathered and verified to ensure that it contained all the hazard groups and hazardous events. The MRT construction safety system is divided into nine hazard groups: falls from height; falling objects; manual handling; equipment machinery and tools; electricity; slips and trips; fire and explosions; ergonomic/human factors; and noise and vibration. Each hazard group includes several identified hazardous events and is described below.

(1) *Falls from height* includes seven hazardous events: working platform (FH-00001), erection of scaffolding (FH-00002,) cranes (FH-00003), temporary ladder (FH-00004), hole in the ground (FH-00005), working on height unprotected (FH-00006), and roof work (FH-00007).

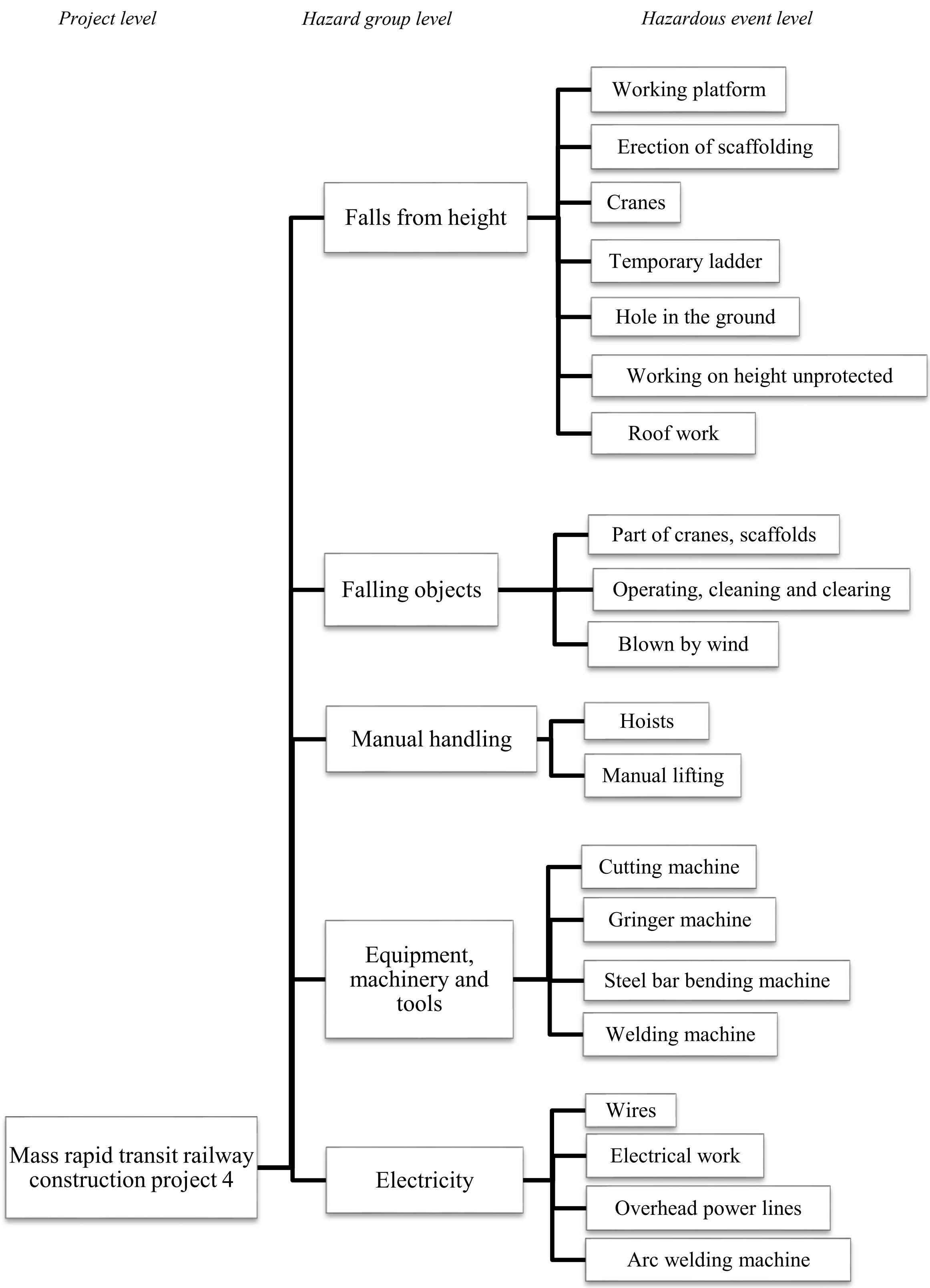
(2) *Falling objects* includes three hazardous events: part of cranes, scaffolds (FO-00008), operating, cleaning and clearing (FO-00009) and blown by wind (FO-00010).

(3) *Manual handling* includes two hazardous events: hoists (MH-00011) and manual lifting (MH-00012).

(4) *Equipment machinery and tools* includes four hazardous events: cutting machine (EQ-00013), steel bar bending machine (EQ-00014), grinder machine (EQ-00015) and welding machine (EQ-00016).

(5) *Electricity* includes four hazardous events: wires (EL-00017), electrical work (EL-00018), overhead power lines (EL-00019) and arc welding machine (EL-00020).

(6) *Slips and trips* includes four hazardous events: tripping over platform building materials (ST-00021), slipping on wet surfaces (ST-00022), trips caused by small change in level (ST-00023) and trips caused by water pipes, rebar (ST-00024).


Project level
Hazard group level
Hazardous event level
Mass rapid transit railway construction project 4
Falls from height
Working platform
Erection of scaffolding
Cranes
Temporary ladder
Hole in the ground
Working on height unprotected
Roof work
Falling objects
Part of cranes, scaffolds
Operating, cleaning and clearing
Blown by wind
Manual handling
Hoists
Manual lifting
Equipment, machinery and tools
Cutting machine
Gringer machine
Steel bar bending machine
Welding machine
Electricity
Wires
Electrical work
Overhead power lines
Arc welding machine

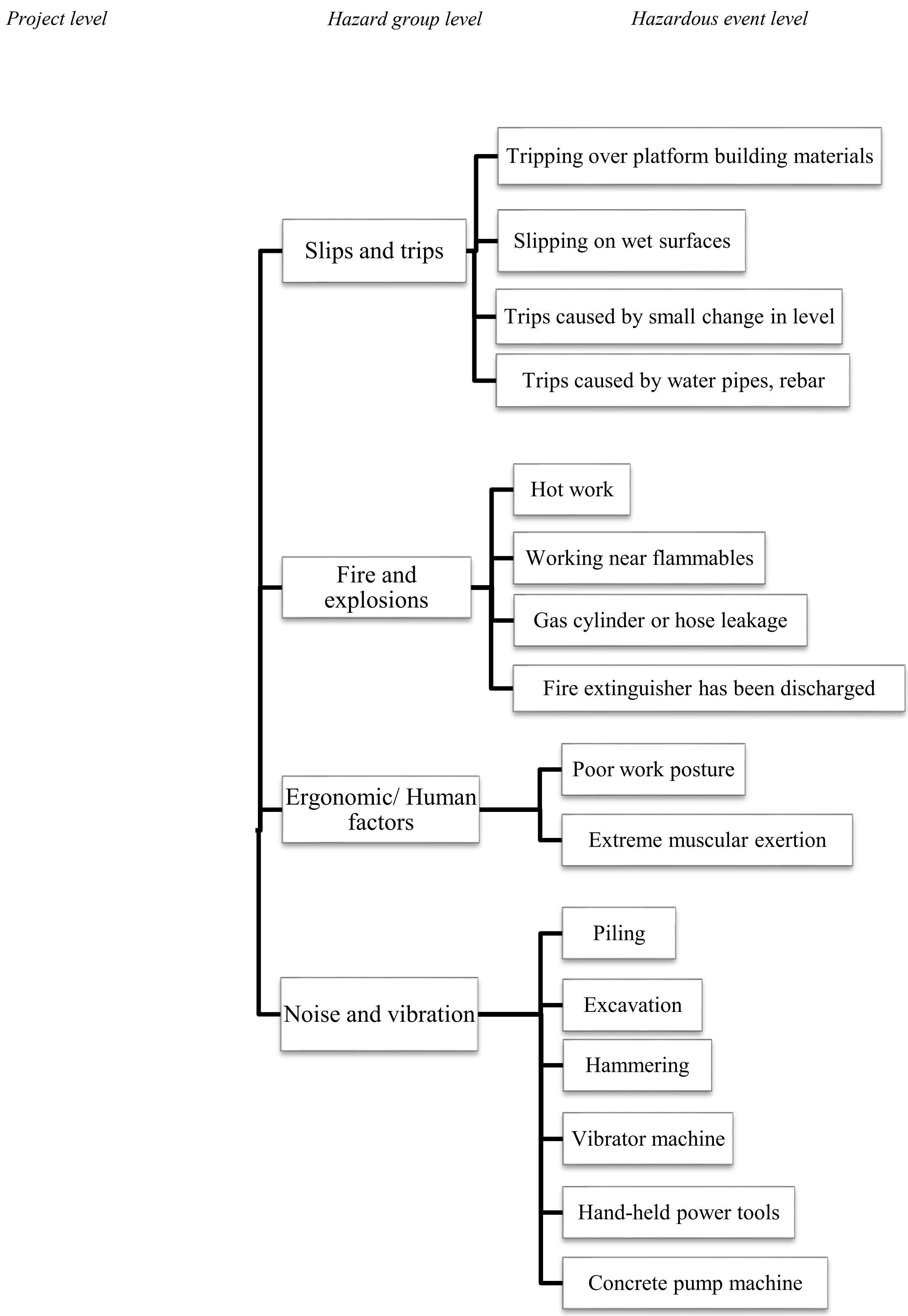


Figure 7-14: Hazard identification at MRT railway construction project 4

(7) *Fire and explosions* includes four hazardous events: hot work (FE-00025), working near flammables (FE-00026), gas cylinder or hose leakage (FE-00027) and fire extinguisher has been discharged (FE-00028).

(8) *Ergonomic and human factors* includes two hazardous events: poor work posture (EH-00029) and extreme muscular exertion (EH-00030).

(9) *Noise and vibration* includes six hazardous events, i.e. piling (NV-00031), excavation (NV-00032), hammering (NV-00033), vibrator machine (NV-00034), hand-held power tools (NV-00035) and concrete pump machine (NV-00036).

7.5.4 Safety Risk Estimation

As the safety risk management process of MRT railway construction project 4 is similar to the case study on the safety risk management of building construction project 1, 2 and 3, the linguistic variables of the risk parameters, PC, PO and SC, and the fuzzy rule base were employed in this case. Once the safety risk criteria were established and the data on PO, SC and PC were calculated using fuzzification, fuzzy aggregation, fuzzy inference, and defuzzification, the safety risk magnitude of all the hazardous events of the MRT railway construction project 4 could be obtained, as shown in Table 7-29.

To assess the overall safety risk magnitude of project 4, the weights of the hazard groups were estimated by using MFAHP based on trapezoidal fuzzy number. Consequently, the overall safety risk magnitude of MRT railway construction project 4 is 2.13 and is in the *Average* category with confidence of 100 per cent, as shown in Table 7-30.

Table 7-29: Safety risk magnitude of MRT railway construction project 4

Hazard groups	Hazardous events	Aggregated STFN: Probability of occurrence	Aggregated STFN: Severity of consequence	Aggregated STFN: Probability of consequence	Safety risk scores	Safety risk categories
Falls from height	FH-00001 Working platform	1.00, 1.00, 1.00, 1.00	1.91, 1.91, 2.13, 2.13	2.97, 2.97, 2.97, 2.97	1.50	Acceptable: 100%
	FH-00002 Erection of scaffolding	1.00, 1.00, 1.22, 1.22	1.69, 1.69, 1.91, 1.91	3.33, 3.33, 3.33, 3.33	2.27	Average: 100%
	FH-00003 Cranes	1.00, 1.00, 1.25, 1.25	1.47, 1.47, 1.69, 1.69	2.30, 2.30, 2.30, 2.30	1.50	Acceptable: 100%
	FH-00004 Temporary ladder	1.00, 1.00, 1.00, 1.00	1.47, 1.47, 1.69, 1.69	2.58, 2.58, 2.58, 2.58	1.50	Acceptable: 100%
	FH-00005 Hole in the ground	1.00, 1.00, 1.00, 1.00	1.94, 2.16, 2.16, 2.38	2.05, 2.05, 2.05, 2.05	1.50	Acceptable: 100%
	FH-00006 Working on height unprotected	1.97, 1.97, 2.44, 2.44	1.94, 2.41, 2.41, 2.88	3.41, 3.41, 3.41, 3.41	2.90	Average: 100%
	FH-00007 Roof work	1.22, 1.22, 1.22, 1.22	2.16, 2.41, 2.63, 2.88	3.30, 3.30, 3.30, 3.30	2.40	Average: 100%
Falling objects	FO-00008 Part of climbing cranes	1.28, 1.28, 1.28, 1.28	1.66, 1.66, 1.88, 1.88	3.19, 3.19, 3.19, 3.19	2.19	Average: 100%
	FO-00009 Operating, cleaning	2.33, 2.33, 2.80, 2.80	1.66, 1.66, 1.88, 1.88	3.44, 3.44, 3.44, 3.44	2.78	Average: 100%
	FO-00010 Blown by wind	1.42, 1.42, 1.42, 1.42	1.66, 1.66, 1.88, 1.88	2.89, 2.89, 2.89, 2.89	1.50	Acceptable: 100%
Manual handling	MH-00011 Hoists	1.00, 1.00, 1.00, 1.00	1.91, 1.91, 1.91, 1.91	2.47, 2.47, 2.47, 2.47	1.50	Acceptable: 100%
	MH-00012 Manual lifting	1.28, 1.28, 1.28, 1.28	1.39, 1.61, 1.61, 1.83	3.50, 3.50, 3.50, 3.50	2.07	Average: 100%
Equipment, machinery and tools	EQ-00013 Cutting machine	1.42, 1.42, 1.42, 1.42	2.05, 2.05, 2.52, 2.52	3.78, 3.78, 4.00, 4.00	1.50	Acceptable: 100%
	EQ-00014 Steel bar bending machine	1.42, 1.42, 1.42, 1.42	1.66, 1.66, 2.13, 2.13	2.75, 2.75, 2.97, 2.97	1.50	Acceptable: 100%
	EQ-00015 Grinder machine	1.42, 1.42, 1.64, 1.64	2.05, 2.05, 2.52, 2.52	4.08, 4.08, 4.08, 4.08	1.50	Acceptable: 100%
	EQ-00016 Welding machine	1.28, 1.28, 1.50, 1.50	1.36, 1.36, 1.83, 1.83	3.69, 3.69, 3.69, 3.69	2.10	Average: 100%
Electricity	EL-00017 Wires	1.00, 1.00, 1.00, 1.00	1.00, 1.00, 1.22, 1.22	1.80, 1.80, 1.80, 1.80	1.50	Acceptable: 100%
	EL-00018 Electrical work	1.00, 1.00, 1.00, 1.00	1.00, 1.00, 1.22, 1.22	2.19, 2.19, 2.19, 2.19	1.50	Acceptable: 100%
	EL-00019 Overhead power lines	1.22, 1.22, 1.69, 1.69	2.08, 2.08, 2.30, 2.30	2.69, 2.69, 2.94, 2.94	1.91	Acceptable: 18%, Average: 82%
	EL-00020 Arc welding machine	1.00, 1.00, 1.00, 1.00	1.00, 1.00, 1.22, 1.22	2.55, 2.55, 2.55, 2.55	1.50	Acceptable: 100%
Slips and trips	ST-00021 Tripping over building materials	2.14, 2.36, 2.61, 2.83	1.64, 1.64, 2.11, 2.11	3.69, 3.69, 3.69, 3.69	1.50	Acceptable: 100%
	ST-00022 Slipping on wet surfaces	2.50, 2.50, 2.72, 2.72	1.64, 1.64, 1.86, 1.86	3.69, 3.69, 3.69, 3.69	1.50	Acceptable: 100%
	ST-00023 Trips caused by small change	2.50, 2.50, 2.72, 2.72	1.64, 1.64, 1.86, 1.86	4.19, 4.19, 4.41, 4.41	1.50	Acceptable: 100%
	ST-00024 Trips caused by water pipes	1.14, 1.14, 1.36, 1.36	1.89, 2.11, 2.11, 2.33	3.94, 3.94, 3.94, 3.94	2.79	Average: 100%
Fire and explosions	FE-00025 Hot work	1.00, 1.00, 1.00, 1.00	1.91, 1.91, 2.13, 2.13	2.55, 2.55, 2.55, 2.55	1.50	Acceptable: 100%
	FE-00026 Working near flammables	1.00, 1.00, 1.00, 1.00	1.66, 1.66, 1.88, 1.88	1.80, 1.80, 1.80, 1.80	1.50	Acceptable: 100%
	FE-00027 Gas cylinder or hose leakage	1.00, 1.00, 1.00, 1.00	1.44, 1.66, 1.66, 1.88	1.80, 1.80, 1.80, 1.80	1.50	Acceptable: 100%
	FE-00028 Fire extinguisher discharged	1.00, 1.00, 1.00, 1.00	1.66, 1.66, 1.66, 1.66	1.80, 1.80, 1.80, 1.80	1.50	Acceptable: 100%

Hazard groups	Hazardous events	Aggregated STFN Probability of occurrence	Aggregated STFN Severity of consequence	Aggregated STFN Probability of consequence	Safety risk scores	Safety risk categories
Ergonomic / Human factors	EH-00029 Poor work posture	1.39, 1.39, 1.61, 1.61	1.75, 1.75, 2.22, 2.22	3.33, 3.33, 3.55, 3.55	2.11	Average: 100%
	EH-00030 Extreme muscular exertion	1.39, 1.39, 1.86, 1.86	1.75, 1.75, 2.22, 2.22	4.08, 4.08, 4.30, 4.30	2.44	Average: 100%
Noise and vibration	NV-00031 Piling	1.00, 1.00, 1.00, 1.00	1.66, 1.66, 1.88, 1.88	2.19, 2.19, 2.41, 2.41	1.50	Acceptable: 100%
	NV-00032 Excavation	1.00, 1.00, 1.00, 1.00	1.66, 1.66, 1.88, 1.88	2.19, 2.19, 2.41, 2.41	1.50	Acceptable: 100%
	NV-00033 Hammering	1.00, 1.00, 1.00, 1.00	1.66, 1.66, 1.88, 1.88	2.19, 2.19, 2.19, 2.19	1.50	Acceptable: 100%
	NV-00034 Vibrator machine	1.00, 1.00, 1.00, 1.00	1.66, 1.66, 1.88, 1.88	1.97, 1.97, 2.19, 2.19	1.50	Acceptable: 100%
	NV-00035 Hand-held power tools	1.00, 1.00, 1.00, 1.00	1.66, 1.66, 1.88, 1.88	1.44, 1.44, 1.66, 1.66	1.50	Acceptable: 100%
	NV-00036 Concrete pump machine	1.00, 1.00, 1.00, 1.00	1.44, 1.44, 1.66, 1.66	1.44, 1.44, 1.44, 1.44	1.50	Acceptable: 100%

Table 7-30: Safety risk magnitude of hazard group in MRT railway construction project 4

System	Hazard groups	Hazard group scores	Weight factors	Hazard group categories
MRT construction project 4 (2.13, Average: 100%)	Falls from height	2.18	0.292	Average: 100%
	Falling objects	2.25	0.196	Average: 100%
	Manual handling	2.07	0.106	Average: 100%
	Equipment, machinery and tools	2.25	0.105	Average: 100%
	Electricity	1.91	0.097	Acceptable: 18%, Average: 82%
	Slips and trips	2.79	0.055	Average: 100%
	Fire and explosions	1.50	0.067	Acceptable: 100%
	Ergonomic/ Human factors	2.44	0.037	Average: 100%
	Noise and vibration	1.50	0.040	Acceptable: 100%

7.5.5 Safety Risk Ranking

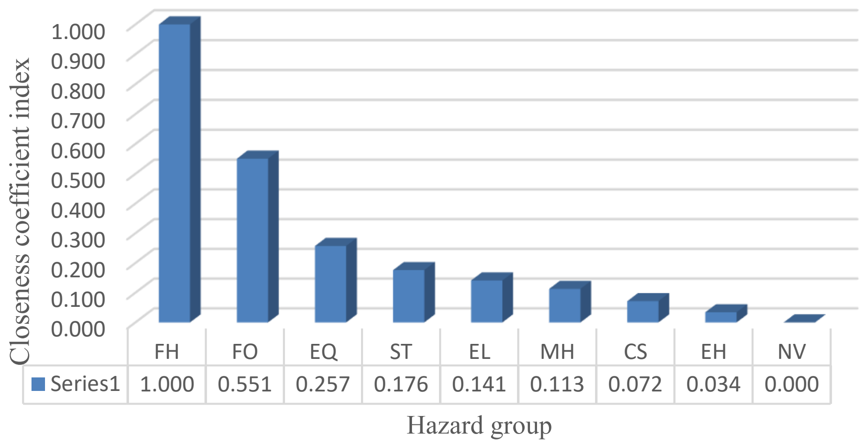
The weight factors were estimated by using the MFAHP and FTOPSIS methods to obtain the final ranking for the evaluating important safety risks. The results of the calculation of the CC_i^* index of all nine hazard groups are presented in Table 7-31.

Table 7-31: Calculation of fuzzy closeness coefficient for each hazard group in MRT railway construction project 4

Hazard groups	Normalised fuzzy	Weighted normalised	$d+$	$d-$	CC_i^*	*Rank*
FH	0.544, 0.676, 0.837, 1.000	0.159, 0.198, 0.245, 0.293	0.0000	0.4445	1.0000	1
FO	0.555, 0.555, 0.756, 0.756	0.109, 0.109, 0.149, 0.149	0.2011	0.2466	0.5509	2
MH	0.260, 0.301, 0.301, 0.342	0.028, 0.032, 0.032, 0.036	0.3949	0.0502	0.1128	6
EQ	0.496, 0.496, 0.704, 0.704	0.052, 0.052, 0.074, 0.074	0.3307	0.1146	0.2573	3
EL	0.285, 0.285, 0.477, 0.477	0.028, 0.028, 0.046, 0.046	0.3823	0.0628	0.1411	5
ST	0.717, 0.717, 0.931, 0.931	0.040, 0.040, 0.052, 0.052	0.3668	0.0783	0.1760	4
EH	0.203, 0.203, 0.227, 0.227	0.014, 0.014, 0.015, 0.015	0.4297	0.0152	0.0341	8
CS	0.414, 0.414, 0.741, 0.741	0.016, 0.016, 0.028, 0.028	0.4132	0.0318	0.0715	7
NV	0.152, 0.152, 0.189, 0.189	0.006, 0.006, 0.008, 0.008	0.4445	0.0000	0.0000	9

7.5.6 Safety Risk Controls and Discussions

The overall safety magnitude of MRT railway construction project 4 is 2.13 and is in the *Average* category with confidence of 100 per cent. Nine identified hazard groups affected the overall safety risk magnitude of MRT construction project 4. It should be highlighted that the results of the proposed model in Table 7-31 revealed that FH, FO, MH, and ST are the highest-ranking hazard groups. Conversely, NV and EH hazard are the lowest-ranking hazard groups. The ranking of the contributions of all nine hazard groups in MRT construction project 4 in Table 7-31, are presented in Figure 7-15.



	FH	FO	EQ	ST	EL	MH	CS	EH	NV
Series1	1.000	0.551	0.257	0.176	0.141	0.113	0.072	0.034	0.000

Figure 7-15: Ranking of all hazard groups in MRT railway construction project 4 to CC_i^* index

Recommended measures for each hazard group with the most important safety risk are presented and discussed below.

Falls from height has six hazardous events: working platform, erection of scaffolding; cranes; temporary ladder; hole in the ground; working on height unprotected; and roof work. To mitigate the probability and severity of consequence, adequate safety instruction, safety information and training should be provided for workers, and it should be ensured that is suitably planned, organised, and supervised. Furthermore, equipment for working at height should be inspected regularly, and emergency procedures should be in place to ensure that physical fall prevention devices used by workers are properly maintained and used as prescribed. The procedures must enable the rescue of an employee in the event of a fall and ensure that first aid is provided to a worker who has fallen as soon as possible after the emergency situation arises.

Falling objects is one of the most common sources of construction project injuries. This hazard group has three hazardous events: part of climbing cranes, scaffolds; operating, cleaning and clearing; and blown by wind. To avoid falling objects due to piling and substructure works, pipes should be stored horizontally and use stoppers to avoid the pipes rolling. Furthermore, rope should be used to hold the pipes together, boards, iron plates, stone plates should be secure tightly to the wall if they are stored vertically and containers should not be stored taller than a person as well as provision of net to cover the scaffolding, the toe board should be used. Moreover, gaps between scaffold boards should be minimised and safety helmet to be worn by all personnel on site.

Slips and trips has four hazardous events: tripping over building materials, slipping on wet surfaces, trips caused by small change and trips caused by water pipes. To reduce and control the safety risk magnitude of MRT railway construction project 4, keeping the workplaces clean and tidy, placing the waste and materials in demarcated areas, displaying warning signs and providing safety shoes required. Furthermore, adequate lighting and handrails should be provided where necessary, there should be no wet floor in the vicinity of the drilling rod, and the working platform and access should be kept free of oil and grease. Clear warning signs and instructions should be displayed in the working areas to enhance the safety awareness of the workers.

Although the hazard groups make a minor contribution to the overall safety risk magnitude of MRT railway construction project 4, the hazardous events in the noise and vibration and ergonomic/human factors hazard groups still need be controlled and monitored. The noise and vibration has six hazardous events: piling, excavation, hammering, vibrator machine, hand-held power tools and concrete pump machine. Measures should be implemented to safety risks related to noise and vibration, information, instruction and training should be provided and health surveillance should be provided where there is a risk to health. Where possible, the source of noise should be mitigated. Noise can be reduced by improving the construction or work procedures. Where mitigation cannot to be carried out, it should be controlled. Finally, the correct hearing protection should be provided if the noise exposure cannot be reduced using other methods.

The results of the proposed construction safety risk management model are compared with the results of MRT railway construction project 4's method, as shown in Table 7-32. It can be noted that the safety risk ranking in the proposed construction safety risk assessment model is slightly different from that of the project's method. For example, in the proposed model, falls from height (working on height unprotected) has a safety risk score of 2.90 and is in the *Average* category with confidence of 100 per cent. In MRT railway construction project 4's method, however, it has a safety risk level of *Medium*, and the hazardous events are in a similar position in both methods. Nevertheless, the MRT railway construction project 4's method cannot provide more safety risk information to the safety risk expert team for the purposes of decision-making. Therefore, it should be highlighted that the proposed construction safety management model can be applied in MRT or railway construction and can provide safety risk information and produce safety risk ranking similar to the risk level estimated by MRT railway construction project 4's method.

Table 7-32: Safety risk level of MRT railway construction project 4

Proposed Construction Safety Risk Management Method			MRT construction project 4's Method
Hazardous events	Risk Score	Safety risk categories	Risk level
FH-06 Working on height unprotected	2.90	Average:100%	Medium
ST-24 Trips caused by rebar	2.79	Average:100%	Medium
FO-09 Operating, cleaning and clearing	2.78	Average:100%	Medium
EH-30 Extreme muscular exertion	2.44	Average:100%	Medium
FH-07 Roof work	2.40	Average:100%	Medium
FH-02 Erection of scaffolding	2.27	Average:100%	Medium
FO-08 Part of cranes, scaffolds	2.19	Average:100%	Medium
EH-29 Poor work posture	2.11	Average:100%	Medium
EQ-16 Welding machine	2.10	Average:100%	Medium
MH-12 Manual lifting	2.07	Average:100%	Medium
EL-19 Overhead power lines	1.91	Acceptable:18%, Average:82%	Medium
FH-01 Working platform	1.50	Acceptable:100%	Medium
FH-03 Cranes	1.50	Acceptable:100%	Medium
FH-04 Temporary ladder	1.50	Acceptable:100%	Medium
FH-05 Hole in the ground	1.50	Acceptable:100%	Medium
FO-10 Blown by wind	1.50	Acceptable:100%	Low
MH-11 Hoists	1.50	Acceptable:100%	Medium
EQ-13 Cutting machine	1.50	Acceptable:100%	Low
EQ-14 Steel bar bending machine	1.50	Acceptable:100%	Low
EQ-15 Grinder machine	1.50	Acceptable:100%	Low
EL-17 Wires	1.50	Acceptable:100%	Low
EL-18 Electrical work	1.50	Acceptable:100%	Medium
EL-20 Arc welding machine	1.50	Acceptable:100%	Low
ST-21 Tripping over building materials	1.50	Acceptable:100%	Low
ST-22 Slipping on wet surfaces	1.50	Acceptable:100%	Low
ST-23 Trips caused by small change	1.50	Acceptable:100%	Low
FE-25 Hot work	1.50	Acceptable:100%	Medium
FE-26 Working near flammables	1.50	Acceptable:100%	Low
FE-27 Gas cylinder or hose leakage	1.50	Acceptable:100%	Low
FE-28 Fire extinguisher has been discharged	1.50	Acceptable:100%	Low

Table 7-32: (Continued)

Proposed Construction Safety Risk Management Method			MRT construction project 4's Method
Hazardous events	Safety risk score	Safety risk categories	Risk level
NV-31 Piling	1.50	Acceptable:100%	Low
NV-32 Excavation	1.50	Acceptable:100%	Low
NV-33 Hammering	1.50	Acceptable:100%	Low
NV-34 Vibrator machine	1.50	Acceptable:100%	Low
NV-35 Hand-held power tools	1.50	Acceptable:100%	Low
NV-36 Concrete pump machine	1.50	Acceptable:100%	Low

7.6 Summary

This chapter discussed four applied case studies on safety risk assessment and management of building and MRT railway construction projects. The FRT, MFAHP and FTOPSIS methods were used in the proposed construction safety risk management model. It can be noted that the proposed construction safety risk management model can be applied in either building construction or MRT construction projects to quantitatively and qualitatively assess safety risk.

The safety risk score of a construction project, hazard groups, hazardous events and type of safety risk can be obtained with a confidence percentage. Moreover, the safety risk ranking of all hazard groups can be obtained, which can be useful information to support effective safety risk decision-making for managing safety hazards and dealing with the overall safety risk of building construction projects. The information provided for the case studies covers the safety risks in each construction project based on the results obtained for the important hazard groups. These results will be discussed in depth in the Chapter 8.

CHAPTER EIGHT

DISCUSSION

8.1 Introduction

This chapter discusses the research findings from the development of the proposed construction safety risk management model based on the FRT, MFAHP and FTOPSIS methods. The strengths and weaknesses of the proposed model are presented. Following this, the achievements in the study and limitations of the research are explained.

8.2 Findings

The discussion of the findings is based on the results provided in Chapters 2, 4, 5, 6, and 7. It is helpful to divide the findings into the following sections: literature review, survey programme, development of the safety risk management model and case studies.

8.2.1 Literature Review

There is no doubt that working on a construction site is inherently dangerous, and this needs to be improved according to the statistics on major accidents that have been occurred in the construction industry, as described in Chapter 2. The leading causes of death and injury on construction sites include: falls from height; falling objects; manual handling; equipment, machinery and tools; electricity; slips and trips; traffic hazards; vehicle overturn; fire and explosions; exposure to hazardous substances; radiation hazards; collapse of site structure; ergonomic/human factors; confined spaces; and noise and vibration. Based on confirmation of the safety risks identified by the project managers, safety managers and project engineers, it was revealed that falls from height and falling objects are the most common critical hazards in construction projects. The findings are in line with the those of Zhou and Pang (2013), which were that falling injuries during construction are one of the most frequent accidents in the construction industry and have a higher incident rate than in other industries. The same result was obtained by Huang and Hinze (2003), who report that falls from height has been ranked in the top 10 with the highest frequency amongst construction accidents compared with other types of accident, such as falling objects, contact with electricity, and vehicle collisions. It was revealed that lack of awareness and ignorance of workers are the main causes of accidents on building construction projects (Limsupreeyarat et al., 2010). Therefore, there is an urgent need for appropriate and effective prevention of these accidents.

8.2.2 Survey Programme

Major statistics on construction accidents have been presented and summarised in this thesis based on the statistics on major accidents. The literature shows, however, that little work has been done on construction safety risk assessment and management in Thailand, and there is very little available data to support this research. Therefore, a survey programme was employed to identify and confirm the safety risks which have been identified as the major safety risks the industry faces.

For allocating the safety risks mentioned in the survey programme to more detailed and specified level of importance, the top four safety risks were proposed by the respondents for this research as follows:

1. Falls from height = Very importance
2. Falling objects = Major
3. Equipment, machinery and tools= Major
4. Electricity = Major

It has been ascertained that among the four major safety risks, falls from height has the highest level of safety risk in construction projects, followed by falling objects and equipment, machinery and tools, and electricity (Aminbakhsh et al., 2013; Zhou and Pang, 2013; Mistikoglu et al., 2015;).

The findings also revealed one of the reasons for not using statistical methods to assess safety risks. Some respondents explained that most construction sites have limited resources such as time, technical equipment, and skilled personnel. Furthermore, the qualitative risk assessment technique is the easiest tool to analyse the safety risk, which is one process for assessing the severity and likelihood of the identified safety risks (Modarres, 2006) as there is no need to do complicated calculations. The quantitative risk assessment technique is a formalised specialist method for calculating the safety risk level which uses numerical measures to estimate the probability of occurrence and severity of consequence. This is why this method is generally employed in medium and large construction project companies. The findings are in line with those of Nieto-Morote and Ruz-Vila (2011), who argue that as the problems facing the construction industry contain a variety of quantitative and qualitative risk data, including incomplete safety risk data and a high level of uncertainty, the traditional quantitative risk assessment method may not be sufficient to prioritise the safety risk in construction projects. Therefore, it is necessary to develop new construction risk assessment methods to cope with the risks involved in complicated situations.

8.2.3 Development of Safety Risk Management Modelling

A construction safety risk management model has been developed to deal with an uncertain environment and vague information. It includes the steps of safety hazard identification and risk data collection, safety risk criteria calculation, safety risk estimation, safety risk ranking, safety risk control and mitigation, and safety risk monitoring. The main findings in this model are discussed below, see Section 8.2.3.1, 8.2.3.2, 8.2.3.3, 8.2.3.4.

8.2.3.1 Safety hazard identification

Identifying safety risks is the first and most important stage in the safety risk management process on a construction project. There are multiple types of identification methods for formulating those safety risks, including checklists, the 'what if' approach, the brainstorming approach, FMEA, a HAZOP study, CHA, PHA, and JHA. Brainstorming is typically one of the safety risk identification techniques available in the literature on a project site. However, inexperience and the insufficient skill level of the experts can lead to risks for the hazard identification process. Therefore, to ensure that safety risk identification is performed in an adequate and timely way, historical information as a guide to safety hazard identification can provide background information on previous challenges and help to assess hazardous events. The findings are consistent with those of Gajewska and Ropel (2011), which were that experience was considered as an information methods, and that considering the previous projects could be useful sources for identifying potential risks. The events in past projects, historical data from similar projects, and hazard lists provide valuable insight into future safety risks for consideration of hazards.

8.2.3.2 Safety risk criteria calculation

The findings in this study revealed that the standards of qualitative descriptors of probability of occurrence (PO), which refers to the number of times an event occurs or the failure frequencies in a certain time period, are "*Very unlikely*", "*Unlikely*", "*Fairly unlikely*", "*Likely*", and "*Very likely*". For instance, the linguistic term "*Very unlikely*" is used to explain the number of times an event occurred with a nominal value of four-five times every six months. In specific construction projects, however, the standards of qualitative descriptors can be changed based on historical data and information.

8.2.3.3 Suggestion of the third parameter

Safety risk has commonly been estimated using two parameters: probability of occurrence (PO) and severity of consequence (SC). They do not take into the probability of current consequence caused in the project safety risk assessment process. Nonetheless, considering the safety magnitude of a particular safety risk depends highly upon the probability that the accident will occur. Therefore, this research incorporated a third parameter, probability of consequence (PC), into the proposed construction safety risk management model to obtain more accurate and reliable results of safety risk analysis. It should be noted that the safety risk level without considering PC might be high; however, if the probability is very low, this might not be the case. For example, in scenario 2 parameters, the PO of many people working at height is *Very likely* and the SC is *Catastrophic*; therefore, the safety risk level will be estimated as *Unacceptable*. On the other hand, in scenario 3 parameters, the PO of many people working at height is also *Very likely* and the SC is also *Catastrophic* and the PC (added third parameter) is judged to be *Unlikely*; therefore, the safety risk level of working at height will be downgraded as *Medium*. This means this work can keep the process going; however, a control plan must be developed and should be implemented as soon as possible.

8.2.3.4 Technique for hazard group ranking

Hazard group ranking is a considerable part of the process of safety risk management. More important hazard groups were classified in different safety risk ranking to propose efficient safety risk mitigation measures. However, the MCDM methodology by using FRT, MFAHP and FTOPSIS is a hybrid application for solving problems with existing inherent uncertainty.

This technique makes the proposed model more accurate, and reliable, and a realistic approach to prioritising the solutions.

The findings in this study also revealed that the proposed model was developed using the FRT to cope with the uncertainties, subjectivity and vagueness that arise during construction projects, and then an MFAHP was used to create appropriate weightings. This method is useful when dealing with a huge amount judgemental information as it reduces the uncertainty associated with experts' judgements. Finally, the FTOPSIS method was used to solve the problems under the fuzzy environment to obtain the ranking of the safety risk on construction sites. According to Taylan et al. (2014), "The fuzzy TOPSIS method is very suitable for solving group decision making problems under vague and fuzzy environments in construction projects". This finding supports the finding of Abdullah and Zulkifli (2015), which was that fuzzy AHP has been used to obtain the relative weights of criteria when weights are imprecise, and uncertain and contain ambiguous information. Therefore, it was observed that these comprehensive methodologies are very suitable and flexible for various decision situations.

8.2.4 Case Studies

The proposed model was applied in four real construction case studies in Thailand, and the performance of this model under vague and fuzzy environments was evaluated and validated. Three case studies on safety risk assessment and management of building construction projects and one case study on an MRT railway construction project were conducted. The findings from all the case studies revealed that risk levels have different safety risk magnitudes based on different projects' situations and features regarding the scale and type of projects. To demonstrate these differences, an illustrative comparable example is explained in more detail to simulate the projects' safety risk management. The hazard group falls from height is clearly the highest-ranking safety risk. Interestingly, it was found that five hazard groups, fallings from height, falling objects, manual handling, equipment machinery and tool, and electricity were ranked in the top five hazard groups in all the case studies, as illustrated in Figures 7-10, 7-13, 7-16, and 7-19, and Tables 7-14, 7-22, 7-27, and 7-31 respectively. Furthermore, the results obtained for one of the hazard events in the falls from height group were compared with the safety risk scores for the four case studies, which are 2.61, 2.00, 3.32, and 1.50 respectively. MRT railway construction project 4 is different from the other three building construction projects. For example, falls from height (working platform) has a safety risk score of 1.50 and an *Acceptable* level of safety risk with confidence of 100 per cent, which clearly illustrates the differences in site configuration and project stages. The project is not complex and the building is a four storey structure, which is 15-18 metres in high, and the project consists of a concourse and platform levels in the station. The project is strongly committed to the promotion of risk management practices. Therefore, the mitigation and control of safety risks regarding falls from height was minimal, such as edges and holes of the platform were fitted with effective guardrails and toe boards. Safety training and instruction on using devices regarding falls from height was provided for the workers, full harnesses and fall-arresting devices were provided. Moreover, competent workers with experience in working at height were engaged. Furthermore, warning notices and safety toolbox meetings were used to improve safety awareness on the construction site. The results from building construction projects 1, 2, and 3 are 2.00-3.32, as due to the wearing of PPE such as a safety harnesses, hardhat and safety shoes, very few hazardous events were reported at building construction project 3. Moreover, three building construction project 1, 2 and 3 had more than 30 storeys, were complex building construction projects, and had more than

300 construction workers including contractors and subcontractors. Therefore, the overall safety risk comparison of the hazardous event for the construction projects clearly represent the situation for the four projects and the mitigation and control safety risks in their safety risk management. To improve the SSOP during the construction projects, they require different mitigation actions based on their risk level and condition.

Interestingly, although all four construction projects have different safety risk scores, PPE, such as safety harnesses and safety shoes was a control measure that was used to cope with safety risks in all four projects. However, PPE should be worn when all the previous protection measures are unavailable or have been found to be ineffective in controlling safety risks to a reasonably practicable level. Surprisingly, someone workers refuse to wear PPE on construction sites as they do not understand why they need to wear it and consider it inconvenient. These reasons have been found through observations and interviews. In this case, proper safety training on the safety risk for workers must be provided. According to the comparison of hazardous events, the proposed construction safety risk management model is more reliable and less ambiguous methodology for effective safety risk management of construction projects.

8.3 Achievements in the Study

Based on the case study materials from the real construction projects that were provided by companies, the proposed construction safety risk management model was developed using a combination of the FRT, MFAHP and FTOPSIS methods. It should be noted that this proposed construction safety risk management model is not only for building construction projects, but can also be widely applied in other construction projects, such as railway construction projects, highway construction projects, airport construction projects, and bridge construction projects.

Furthermore, in many circumstances, the most common causes of major injuries in a construction project in Thailand should be recognisable in other construction projects. Consequently, the findings of this research based on four case studies suggest effective mitigation and control actions for elimination, substitution, engineering controls, administrative controls, and PPE in the significant hazard groups before they take place. They can provide useful safety information on building construction project management regarding poor construction project performance.

8.4 Contribution to Knowledge

The main outcome of this research is the advancement of knowledge regarding the application of safety risk management to construction safety management projects.

The proposed safety risk management model is developed based on FRT, MFAHP and FTOPSIS methods, where the potential safety risk in construction safety management is assessed in terms of PO, SC and PC. It is quite appropriate for the circumstances where some risk events happen frequently and may possibly lead to serious consequences depending on the existing safety risk measures. The third parameter, PC, was incorporated into the proposed model to obtain more accurate and reliable results of safety risk analysis in the construction industry. The PC can be derived from expert judgement, and experts can provide a crisp value, a range of numbers or subjective judgments, based on their expert knowledge and information.

The combination of the FRT, MFAHP and FTOPSIS methods to deal with uncertainties in construction projects contributes significantly to construction safety management projects and can be utilised to analyse and manipulate the safety risk level of every possible hazardous event that is identified before starting a project or during the construction period. Furthermore, the proposed safety risk management model can be applied to any industries which depend on the types and sizes of the projects, such as buildings, dams, bridges and roads which can change the specific safety risks.

Four practical case studies are employed to fill the gap between the knowledge and practice to illustrate the applicability and performance of the proposed model, and to cope with uncertain and imprecise knowledge. The model per se provides a powerful tool that can be implemented in a construction project.

The most common causes of major injuries in a construction project should be recognisable in other construction projects. Consequently, the findings of this research based on the four case studies suggest implementing effective mitigation and control actions before they take place. They can provide useful safety information on building construction project management regarding poor construction project performance.

8.5 Impact

The improvements made in the safety risk management performance in the building construction industry have an immediate impact on: 1) Practising the theoretical contribution, including the safety risk management concept by professionals involved in construction safety risk management such as project managers, safety officers, engineers and others working in the construction industry, especially when it comes to improving the safety management performance on building construction sites. Although it might not be possible to take this as a textbook formula to ensure a higher level of workplace safety, most players in the construction industry would probably be able to employ the ideas and suggestions for improvements if they were able to adapt them to their own organisational context. (2) Explaining the third parameter, PC, as it discriminates a hazardous event with a higher PC to cause fatalities. This will affect the overall safety risk scores obtained through the combination of the FRT, MFAHP and FTOPSIS techniques to deal with uncertainties in construction projects.

8.6 Summary

This chapter has discussed the research findings of this project. By comparing the findings from the four construction projects, this study has found that safety risk management is based on different situations and different types of projects. Obviously, the construction industry has the greatest risk of being injured as major construction sites can have significant levels of risk. The achievements in this study have been revealed and the knowledge contribution of the research has been provided.

The next chapter, Conclusions and Limitations, presents an overall summary of the thesis. The research project objectives are revisited to determine whether the research aim has been achieved, and recommendations for future studies are made.

CHAPTER NINE

CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The literature review which was conducted in this research has shown that construction remains a high-risk industry despite the downward movement in the number of injuries. It is also no secret that construction can be a dangerous industry. This research project focused on the development of a risk assessment and safety management model for the building construction industry based on the FRT, MFAHP and FTOPSIS methods. The research has shown that the proposed model can assist project managers, safety officers and engineers with decision-making to enable them to manipulate and control safety risks in their safety risk management and improve SSOP during their construction projects. The main achievements of this research are summarised below according to the specific objectives.

OBJECTIVE 1: To examine the current occupational safety problems and investigate the various types of risk.

- Data on accidents in the construction industry was collected from reports, articles and the industry and identify the main types of accident occurring in construction projects. The findings from the data on accidents revealed the most common causes of major injuries and their consequences at construction sites.

- The major statistics on major construction accidents were found and summarized in this thesis, and the data were collected from websites. The findings in this study show that construction workers are more likely at a high risk of injury as result of their works.

OBJECTIVE 2: To undertake a comprehensive literature review to establish potentially viable research routes.

- Potential safety risk assessment methodologies were analysed and classified, and it was found that the FRT, AHP and TOPSIS methods were more suitable to be used in the development of the safety risk analysis model. The literature in the field of safety risk management was reviewed to establish a research framework to be applied in this research. The findings revealed that safety risk assessment and management processes in construction are important. These include the processes concerned with identifying, assessing, ranking, controlling and monitoring project safety risks. The safety risk assessment techniques currently used in the construction industry may not provide satisfactory results, as a hazardous event may be very difficult to establish using a quantitative risk assessment due to the high level of uncertainty involved and incomplete risk information to determine the probability of a possible consequence scenario. Many research studies have provided evidence that the FRT method is employed to deal with imprecise, incomplete safety information in the safety risk assessment within construction, as it can cope with both quantitative and qualitative safety risk data. Regarding the combination of the AHP and TOPSIS methods, it has been shown that the MFAHP can be a useful tool to obtain the weight factors when dealing with many experts' judgements by using the pairwise comparison matrix to provide consistent treatment of such judgements. Moreover, the calculated weights were used in an FTOPSIS procedure to evaluate the important safety risks.

- It can be concluded that in the new safety risk management model, the third parameter, probability of consequence, was incorporated. Currently, the two fundamental risk parameters that are commonly used to assess risk levels in safety assessment of a construction project are probability of occurrence and severity of consequence. These two parameters do not take into account the probability of current consequences caused in the project safety risk assessment process to obtain more accurate and reliable results of safety risk analysis. Therefore, a third parameter, probability of consequence was used in the development of the construction safety risk management model

OBJECTIVE 3: To identify most of the key possible safety risks in the building construction industry

- Survey programme was employed to identify safety risks and concerns within the construction industry. The findings show that falls from height is considered to be a very important safety risk and that falling objects pose a more major safety risk than radiation hazards and noise and vibration, which are common in building construction projects. Regarding the survey programme, it was confirmed by the project managers, safety managers, safety officers and site engineers that the safety risks in the building construction industry comprise: falls from height; falling objects; manual handling; equipment, machinery and tools; electricity; slips and trips; traffic hazards; vehicle overturn; fire and explosions; exposure to hazardous substances; radiation hazards; collapse of site structure; ergonomic/human factors; confined spaces; and noise and vibration.

OBJECTIVE 4: To develop a safety risk management model for risk assessment and an occupational safety management strategy based on FRT, MFAHP and FTOPSIS.

- The data collected were used to define the standards of qualitative descriptors associated with the safety risk management model that was developed for safety risk analysis.

- The third parameter, probability of consequence (PC), was incorporated into the model to obtain more accurate and reliable results of safety risk analysis. Probability of consequence is defined as the occurrence likelihood of the accident if an event becomes a reality. However, the probability of consequence can be derived from experts' judgements based on their knowledge and experience, which usually involves a safety risk assessment team from different disciplines/backgrounds and a high degree of knowledge of the construction activities. The overall safety risk scores from the proposed model have been affected by the probability of consequence with very low of the probability of occurrence but very high of the severity of consequence or very high of probability of occurrence and the severity of consequence or very high of probability of consequence or very low of probability of occurrence and probability of consequence but very high of severity of consequence.

- The proposed safety risk management model was developed by using a combination of the FRT, MFAHP and FTOPSIS methods. It can be used appropriately to estimate, assess, prioritise, control, mitigate, and monitor the potential safety risks in construction projects. The findings revealed that the proposed model can efficiently assess both quantitative and qualitative safety risk data in an uncertain environment with vague information. It can also provide the results of both safety risk scores and types of safety risk with a confidence percentage, including system safety risk levels in terms of safety risk score and safety risk ranking, which provide useful information for project managers, safety managers and site engineers and enable them to improve their safety risk management and SSOP

- The 15 hazard groups were identified and categorised according to their relative safety risks in the project, and then the final safety risk ranking for the evaluation of important safety risks was obtained by using the MFAHP and FTOPSIS methods. This can provide a safety risk ranking with valuable information for safety risk decision-making where weights are vague and imprecise in construction projects.

OBJECTIVE 5: To verify the reliability of risk assessment and occupational safety management models using case studies.

- The proposed model has been applied in four real construction case studies in Thailand: three building construction projects and one MRT railway construction project. The results show that there are benefits to be gained by using the proposed model. It can provide comprehensive results in the form of safety risk scores in a defined area and safety risk categories with a degree of confidence for the whole construction project, hazard groups and hazardous events. Moreover, the results obtained from the proposed model were compared with the results from existing risk assessment methods used in the case study projects. The findings of all the case study materials reveal similar safety rankings for the association of the hazard groups. However, the results are more reliable than those using the existing construction projects methods, as more parameters were incorporated into the proposed model.

OBJECTIVE 6: To produce an effective and efficient safety risk assessment and management framework that could be accepted by the Thai building industry.

- Group interviews were conducted with experienced construction managers and safety officers, who gave their views on how to manage high safety risks in the Thai construction industry, which can provide safety guidance and tools to improve construction risk management. In this particular projects, as seen from the results, the major hazard group is falls from height, which ranked in first place with a high safety risk level in each of the real construction case studies. Therefore, safety risk mitigation measures must be applied, for example, all work at height must be properly planned and organised, induction safety training on using fall protection devices, safety harnesses and safety belts should be provided. Furthermore, all equipment for working at height must be appropriately inspected, and information concerning personal safety must be provided to construction workers via SSOP, safety risk assessment, and safety toolbox meetings. Finally, warning notices should be displayed in working areas to remind construction workers to follow the safety procedure. Chi et al. (2015) state that primary accident prevention measures should be provided, including fixed barriers such as handrails, guardrails, and surface opening protection and then secondary protection measures should be provided, including safety belts, safety harnesses and safety nets.

9.2 Limitations of the Research

It is important to note the limitations of this research. All research may include some limitations owing to the reasons for conducting this type of study. Therefore, the research limitations are summarised below:

- The findings from this research provide comprehensive results in terms of safety risk levels in defined regions and safety risk categories with the degree of confidence of the construction project system, hazard groups, and hazardous events, and the safety risk ranking of hazard groups. However, it may be difficult to determine the weight factors by using the MFAHP method in pairwise comparison matrices and to obtain the safety risk ranking of the hazardous events using the FTOPSIS method when more than 20 hazardous events need to be compared. It would be useful to deal with this situation in further research.

- The validation of the proposed model is based on ranking the safety risks. In building construction project 3, the proposed model can produce the results for the safety risk magnitude of the hazardous events and hazard groups that are specific to building construction project 3's system. In cases where the safety risk information is not available, some vital information has been hidden. The comprehensive results of the proposed risk management model cannot be compared with the method applied by building construction project 3. However, the results obtained from the proposed model have been proved through discussion with the safety risk management team in building construction project 3.

- The research is based on safety risk management strategies that are applicable or suitable for the building construction industry. While this scope makes the research area feasible and manageable, it can also be considered as a limiting factor. This limitation is influenced by the time span and the need to manage the extended data of safety risk management. However, it should be noted that what works in one country may not work in another. A wider scope for the study area may have capitulated results that could be produced across countries.

9.3 Recommendations for Future Work

Key issues identified by the present study need to be explored further. The first issue relates to the combination of the FRT, MFAHP and FTOPSIS methods to develop the safety risk management model. The research results revealed that when using MFAHP when increasing the number of hazard groups to more than 20 hazard groups, the calculations of pairwise comparison matrices become more complex and may be difficult to carry out. Therefore, in future research, software development is more suitable to facilitate application of the construction safety risk management model to reduce the time taken.

The developed construction safety risk management model and safety risk assessment methodologies are not restricted to the construction industry, but can also apply to multidisciplinary areas, such as warehouse safety, office safety, health risk assessment, maintenance safety, and manufacturing safety.

It will be beneficial if future researchers can apply the combination of FRT, MFAHP and FTOPSIS methods and the involvement of more than six experts' judgements in testing how sound the developed model is. This may produce interesting findings, which will boost the confidence of the researchers on this work. It will encourage the researchers to apply this model to other areas of interest.

9.4 Publications

The research paper "*Development of risk assessment and occupational safety management model for building construction projects*" was presented at the International Conference on

Construction and Civil Engineering (ICCCE 2015) September 25-26, 2015, London, United Kingdom, and was selected for publication in the *International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering* Vol:9, No:9, 2015 are provided in Appendix F.

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APPENDICES

APPENDIX A.

QUESTIONAIRE SURVEY

APPENDIX D.

FUZZY RULE BASE

Rule No	Rule description
Rule #1:	IF PO is *Very unlikely* and SC is *Negligible* and PC is *Highly unlikely* THEN RM is *Low*
Rule #2:	IF PO is *Very unlikely* and SC is *Negligible* and PC is *Unlikely* THEN RM is *Low*
Rule #3:	IF PO is *Very unlikely* and SC is *Negligible* and PC is *Reasonably unlikely* THEN RM is *Low*
Rule #4:	IF PO is *Very unlikely* and SC is *Negligible* and PC is *Likely* THEN RM is *Acceptable*
Rule #5:	IF PO is *Very unlikely* and SC is *Negligible* and PC is *Reasonably likely* THEN RM is *Acceptable*
Rule #6:	IF PO is *Very unlikely* and SC is *Negligible* and PC is *Highly likely* THEN RM is *Acceptable*
Rule #7:	IF PO is *Unlikely* and SC is *Negligible* and PC is *Highly unlikely* THEN RM is *Low*
Rule #8:	IF PO is *Unlikely* and SC is *Negligible* and PC is *Unlikely* THEN RM is *Low*
Rule #9:	IF PO is *Unlikely* and SC is *Negligible* and PC is *Reasonably unlikely* THEN RM is *Acceptable*
Rule#10:	IF PO is *Unlikely* and SC is *Negligible* and PC is *Likely* THEN RM is *Acceptable*
Rule#11:	IF PO is *Unlikely* and SC is *Negligible* and PC is *Reasonably likely* THEN RM is *Acceptable*
Rule#12:	IF PO is *Unlikely* and SC is *Negligible* and PC is *Highly likely* THEN RM is *Average*
Rule#13:	IF PO is *Fairly unlikely* and SC is *Negligible* and PC is *Highly unlikely* THEN RM is *Low*
Rule#14:	IF PO is *Fairly unlikely* and SC is *Negligible* and PC is *Unlikely* THEN RM is *Acceptable*
Rule#15:	IF PO is *Fairly unlikely* and SC is *Negligible* and PC is *Reasonably unlikely* THEN RM is *Acceptable*
Rule#16:	IF PO is *Fairly unlikely* and SC is *Negligible* and PC is *Likely* THEN RM is *Acceptable*
Rule#17:	IF PO is *Fairly unlikely* and SC is *Negligible* and PC is *Reasonably likely* THEN RM is *Average*
Rule#18:	IF PO is *Fairly unlikely* and SC is *Negligible* and PC is *Highly likely* THEN RM is *Average*
Rule#19:	IF PO is *Likely* and SC is *Negligible* and PC is *Highly unlikely* THEN RM is *Acceptable*
Rule#20:	IF PO is *Likely* and SC is *Negligible* and PC is *Unlikely* THEN RM is *Acceptable*
Rule#21:	IF PO is *Likely* and SC is *Negligible* and PC is *Reasonably unlikely* THEN RM is *Acceptable*
Rule#22:	IF PO is *Likely* and SC is *Negligible* and PC is *Likely* THEN RM is *Average*
Rule#23:	IF PO is *Likely* and SC is *Negligible* and PC is *Reasonably likely* THEN RM is *Average*
Rule#24:	IF PO is *Likely* and SC is *Negligible* and PC is *Highly likely* THEN RM is *Average*
Rule#25:	IF PO is *Very likely* and SC is *Negligible* and PC is *Highly unlikely* THEN RM is *Acceptable*
Rule#26:	IF PO is *Very likely* and SC is *Negligible* and PC is *Unlikely* THEN RM is *Acceptable*
Rule#27:	IF PO is *Very likely* and SC is *Negligible* and PC is *Reasonably unlikely* THEN RM is *Average*
Rule#28:	IF PO is *Very likely* and SC is *Negligible* and PC is *Likely* THEN RM is *Average*
Rule#29:	IF PO is *Very likely* and SC is *Negligible* and PC is *Reasonably likely* THEN RM is *Average*
Rule#30:	IF PO is *Very likely* and SC is *Negligible* and PC is *Highly likely* THEN RM is *High*
Rule#31:	IF PO is *Very unlikely* and SC is *Minor* and PC is *Highly unlikely* THEN RM is *Low*

Rule No	Rule description
Rule#32:	IF PO is *Very unlikely* and SC is *Minor* and PC is *Unlikely* THEN RM is *Low*
Rule#33:	IF PO is *Very unlikely* and SC is *Minor* and PC is *Reasonably unlikely* THEN RM is *Acceptable*
Rule#34:	IF PO is *Very unlikely* and SC is *Minor* and PC is *Likely* THEN RM is *Acceptable*
Rule#35:	IF PO is *Very unlikely* and SC is *Minor* and PC is *Reasonably likely* THEN RM is *Acceptable*
Rule#36:	IF PO is *Very unlikely* and SC is *Minor* and PC is *Highly likely* THEN RM is *Average*
Rule#37:	IF PO is *Unlikely* and SC is *Minor* and PC is *Highly unlikely* THEN RM is *Low*
Rule#38:	IF PO is *Unlikely* and SC is *Minor* and PC is *Unlikely* THEN RM is *Acceptable*
Rule#39:	IF PO is *Unlikely* and SC is *Minor* and PC is *Reasonably unlikely* THEN RM is *Acceptable*
Rule#40:	IF PO is *Unlikely* and SC is *Minor* and PC is *Likely* THEN RM is *Acceptable*
Rule#41:	IF PO is *Unlikely* and SC is *Minor* and PC is *Reasonably likely* THEN RM is *Average*
Rule#42:	IF PO is *Unlikely* and SC is *Minor* and PC is *Highly likely* THEN RM is *Average*
Rule#43:	IF PO is *Fairly unlikely* and SC is *Minor* and PC is *Highly unlikely* THEN RM is *Acceptable*
Rule#44:	IF PO is *Fairly unlikely* and SC is *Minor* and PC is *Unlikely* THEN RM is *Acceptable*
Rule#45:	IF PO is *Fairly unlikely* and SC is *Minor* and PC is *Reasonably unlikely* THEN RM is *Acceptable*
Rule#46:	IF PO is *Fairly unlikely* and SC is *Minor* and PC is *Likely* THEN RM is *Average*
Rule#47:	IF PO is *Fairly unlikely* and SC is *Minor* and PC is *Reasonably likely* THEN RM is *Average*
Rule#48:	IF PO is *Fairly unlikely* and SC is *Minor* and PC is *Highly likely* THEN RM is *Average*
Rule#49:	IF PO is *Likely* and SC is *Minor* and PC is *Highly unlikely* THEN RM is *Acceptable*
Rule#50:	IF PO is *Likely* and SC is *Minor* and PC is *Unlikely* THEN RM is *Acceptable*
Rule#51:	IF PO is *Likely* and SC is *Minor* and PC is *Reasonably unlikely* THEN RM is *Average*
Rule#52:	IF PO is *Likely* and SC is *Minor* and PC is *Likely* THEN RM is *Average*
Rule#53:	IF PO is *Likely* and SC is *Minor* and PC is *Reasonably likely* THEN RM is *Average*
Rule#54:	IF PO is *Likely* and SC is *Minor* and PC is *Highly likely* THEN RM is *High*
Rule#55:	IF PO is *Very likely* and SC is *Minor* and PC is *Highly unlikely* THEN RM is *Acceptable*
Rule#56:	IF PO is *Very likely* and SC is *Minor* and PC is *Unlikely* THEN RM is *Average*
Rule#57:	IF PO is *Very likely* and SC is *Minor* and PC is *Reasonably unlikely* THEN RM is *Average*
Rule#58:	IF PO is *Very likely* and SC is *Minor* and PC is *Likely* THEN RM is *Average*
Rule#59:	IF PO is *Very likely* and SC is *Minor* and PC is *Reasonably likely* THEN RM is *High*
Rule#60:	IF PO is *Very likely* and SC is *Minor* and PC is *Highly likely* THEN RM is *High*
Rule#61:	IF PO is *Very unlikely* and SC is *Moderate* and PC is *Highly unlikely* THEN RM is *Low*
Rule#62:	IF PO is *Very unlikely* and SC is *Moderate* and PC is *Unlikely* THEN RM is *Acceptable*

Rule No	Rule description
Rule#63:	IF PO is *Very unlikely* and SC is *Moderate* and PC is *Reasonably unlikely* THEN RM is *Acceptable*
Rule#64:	IF PO is *Very unlikely* and SC is *Moderate* and PC is *Likely* THEN RM is *Acceptable*
Rule#65:	IF PO is *Very unlikely* and SC is *Moderate* and PC is *Reasonably likely* THEN RM is *Average*
Rule#66:	IF PO is *Very unlikely* and SC is *Moderate* and PC is *Highly likely* THEN RM is *Average*
Rule#67:	IF PO is *Unlikely* and SC is *Moderate* and PC is *Highly unlikely* THEN RM is *Acceptable*
Rule#68:	IF PO is *Unlikely* and SC is *Moderate* and PC is *Unlikely* THEN RM is *Acceptable*
Rule#69:	IF PO is *Unlikely* and SC is *Moderate* and PC is *Reasonably unlikely* THEN RM is *Acceptable*
Rule#70:	IF PO is *Unlikely* and SC is *Moderate* and PC is *Likely* THEN RM is *Average*
Rule#71:	IF PO is *Unlikely* and SC is *Moderate* and PC is *Reasonably likely* THEN RM is *Average*
Rule#72:	IF PO is *Unlikely* and SC is *Moderate* and PC is *Highly likely* THEN RM is *Average*
Rule#73:	IF PO is *Fairly unlikely* and SC is *Moderate* and PC is *Highly unlikely* THEN RM is *Acceptable*
Rule#74:	IF PO is *Fairly unlikely* and SC is *Moderate* and PC is *Unlikely* THEN RM is *Acceptable*
Rule#75:	IF PO is *Fairly unlikely* and SC is *Moderate* and PC is *Reasonably unlikely* THEN RM is *Average*
Rule#76:	IF PO is *Fairly unlikely* and SC is *Moderate* and PC is *Likely* THEN RM is *Average*
Rule#77:	IF PO is *Fairly unlikely* and SC is *Moderate* and PC is *Reasonably likely* THEN RM is *Average*
Rule#78:	IF PO is *Fairly unlikely* and SC is *Moderate* and PC is *Highly likely* THEN RM is *High*
Rule#79:	IF PO is *Likely* and SC is *Moderate* and PC is *Highly unlikely* THEN RM is *Acceptable*
Rule#80:	IF PO is *Likely* and SC is *M*oderate and PC is *Unlikely* THEN RM is *Average*
Rule#81:	IF PO is *Likely* and SC is *Moderate* and PC is *Reasonably unlikely* THEN RM is *Average*
Rule#82:	IF PO is *Likely* and SC is *Moderate* and PC is *Likely* THEN RM is *Average*
Rule#83:	IF PO is *Likely* and SC is *Moderate* and PC is *Reasonably likely* THEN RM is *High*
Rule#84:	IF PO is *Likely* and SC is *Moderate* and PC is *Highly likely* THEN RM is *High*
Rule#85:	IF PO is *Very likely* and SC is *Moderate* and PC is *Highly unlikely* THEN RM is *Average*
Rule#86:	IF PO is *Very likely* and SC is *Moderate* and PC is *Unlikely* THEN RM is *Average*
Rule#87:	IF PO is *Very likely* and SC is *Moderate* and PC is *Reasonably unlikely* THEN RM is *Average*
Rule#88:	IF PO is *Very likely* and SC is *M*oderate and PC is *Likely* THEN RM is *High*
Rule#89:	IF PO is *Very likely* and SC is *Moderate* and PC is *Reasonably likely* THEN RM is *High*
Rule #90	IF PO is *Very likely* and SC is *Moderate* and PC is *Highly likely* THEN RM is *Unacceptable*
Rule#91:	IF PO is *Very unlikely* and SC is *Major* and PC is *Highly unlikely* THEN RM is *Acceptable*
Rule#92:	IF PO is *Very unlikely* and SC is *Major* and PC is *Unlikely* THEN RM is *Acceptable*
Rule#93:	IF PO is *Very unlikely* and SC is *Major* and PC is *Reasonably unlikely* THEN RM is *Acceptable*

Rule No	Rule description
Rule#94:	IF PO is *Very unlikely* and SC is *Major* and PC is *Likely* THEN RM is *Average*
Rule#95:	IF PO is *Very unlikely* and SC is *Major* and PC is *Reasonably likely* THEN RM is *Average*
Rule#96:	IF PO is *Very unlikely* and SC is *Major* and PC is *Highly likely* THEN RM is *Average*
Rule#97:	IF PO is *Unlikely* and SC is *Major* and PC is *Highly unlikely* THEN RM is *Acceptable*
Rule#98:	IF PO is *Unlikely* and SC is *Major* and PC is *Unlikely* THEN RM is *Acceptable*
Rule#99:	IF PO is *Unlikely* and SC is *Major* and PC is *Reasonably unlikely* THEN RM is *Average*
Rule#100:	IF PO is *Unlikely* and SC is *Major* and PC is *Likely* THEN RM is *Average*
Rule #101:	IF PO is *Unlikely* and SC is *Major* and PC is *Reasonably likely* THEN RM is *Average*
Rule #102:	IF PO is *Unlikely* and SC is *Major* and PC is *Highly likely* THEN RM is *High*
Rule #103:	IF PO is *Fairly unlikely* and SC is *Major* and PC is *Highly unlikely* THEN RM is *Acceptable*
Rule #104:	IF PO is *Fairly unlikely* and SC is *M*ajor and PC is *Unlikely* THEN RM is *Average*
Rule #105:	IF PO is *Fairly unlikely* and SC is *Major* and PC is *Reasonably unlikely* THEN RM is *Average*
Rule #106:	IF PO is *Fairly unlikely* and SC is *Major* and PC is *Likely* THEN RM is *Average*
Rule #107:	IF PO is *Fairly unlikely* and SC is *Major* and PC is *Reasonably likely* THEN RM is *High*
Rule #108:	IF PO is *Fairly unlikely* and SC is *Major* and PC is *Highly likely* THEN RM is *High*
Rule #109:	IF PO is *Likely* and SC is *Major* and PC is *Highly unlikely* THEN RM is *Average*
Rule #110:	IF PO is *Likely* and SC is *Major* and PC is *Unlikely* THEN RM is *Average*
Rule #111:	IF PO is *Likely* and SC is *Major* and PC is *Reasonably unlikely* THEN RM is *Average*
Rule #112:	IF PO is *Likely* and SC is *Major* and PC is *Likely* THEN RM is *High*
Rule #113:	IF PO is *Likely* and SC is *Major* and PC is *Reasonably likely* THEN RM is *High*
Rule #114:	IF PO is *Likely* and SC is *Major* and PC is *Highly likely* THEN RM is *Unacceptable*
Rule #115:	IF PO is *Very likely* and SC is *Major* and PC is *Highly unlikely* THEN RM is *Average*
Rule #116:	IF PO is *Very likely* and SC is *Major* and PC is *Unlikely* THEN RM is *Average*
Rule #117:	IF PO is *Very likely* and SC is *Major* and PC is *Reasonably unlikely* THEN RM is *High*
Rule #118:	IF PO is *Very likely* and SC is *Major* and PC is *Likely* THEN RM is *High*
Rule #119:	IF PO is *Very likely* and SC is *Major* and PC is *Reasonably likely* THEN RM is *Unacceptable*
Rule #120:	IF PO is *Very likely* and SC is *Major* and PC is *Highly likely* THEN RM is *Unacceptable*
Rule #121:	IF PO is *Very unlikely* and SC is *Catastrophic* and PC is *Highly unlikely* THEN RM is *Acceptable*
Rule #122:	IF PO is *Very unlikely* and SC is *Catastrophic* and PC is *Unlikely* THEN RM is *Acceptable*
Rule #123:	IF PO is *Very unlikely* and SC is *Catastrophic* and PC is *Reasonably unlikely* THEN RM is *Average*
Rule #124:	IF PO is *Very unlikely* and SC is *Catastrophic* and PC is *Likely* THEN RM is *Average*

Rule No	Rule description
Rule #125:	IF PO is *Very unlikely* and SC is *Catastrophic* and PC is *Reasonably likely* THEN RM is *Average*
Rule #126:	IF PO is *Very unlikely* and SC is *Catastrophic* and PC is *Highly likely* THEN RM is *High*
Rule #127:	IF PO is *Unlikely* and SC is *Catastrophic* and PC is *Highly unlikely* THEN RM is *Acceptable*
Rule #128:	IF PO is *Unlikely* and SC is *Catastrophic* and PC is *Unlikely* THEN RM is *Average*
Rule #129:	IF PO is *Unlikely* and SC is *Catastrophic* and PC is *Reasonably unlikely* THEN RM is *Average*
Rule #130:	IF PO is *Unlikely* and SC is *Catastrophic* and PC is *Likely* THEN RM is *Average*
Rule #131:	IF PO is *Unlikely* and SC is *Catastrophic* and PC is *Reasonably likely* THEN RM is *High*
Rule #132:	IF PO is *Unlikely* and SC is *Catastrophic* and PC is *Highly likely* THEN RM is *High*
Rule #133:	IF PO is *Fairly unlikely* and SC is *Catastrophic* and PC is *Highly unlikely* THEN RM is *Average*
Rule #134:	IF PO is *Fairly unlikely* and SC is Catastrophic and PC is *Unlikely* THEN RM is *Average*
Rule #135:	IF PO is *Fairly unlikely* and SC is *Catastrophic* and PC is *Likely* THEN RM is *High*
Rule #136:	IF PO is *Fairly unlikely* and SC is *Catastrophic* and PC is *Reasonably likely* THEN RM is *High*
Rule #137:	IF PO is *Fairly unlikely* and SC is *Catastrophic* and PC is *Highly likely* THEN RM is *Unacceptable*
Rule #138:	IF PO is *Likely* and SC is *Catastrophic* and PC is *Highly unlikely* THEN RM is *Average*
Rule #139:	IF PO is *Likely* and SC is *Catastrophic* and PC is *Unlikely* THEN RM is *Average*
Rule #140:	IF PO is *Likely* and SC is *Catastrophic* and PC is *Unlikely* THEN RM is *Average*
Rule #141:	IF PO is *Likely* and SC is *Catastrophic* and PC is *Reasonably unlikely* THEN RM is *High*
Rule #142:	IF PO is *Likely* and SC is *Catastrophic* and PC is *Likely* THEN RM is *High*
Rule #143:	IF PO is *Likely* and SC is Catastrophic and PC is *Reasonably likely* THEN RM is *Unacceptable*
Rule #144:	IF PO is *Likely* and SC is *Catastrophic* and PC is *Highly likely* THEN RM is *Unacceptable*
Rule #145:	IF PO is *Very likely* and SC is *Catastrophic* and PC is *Highly unlikely* THEN RM is *Average*
Rule #146:	IF PO is *Very likely* and SC is *Catastrophic* and PC is *Unlikely* THEN RM is *High*
Rule #147:	IF PO is *Very likely* and SC is *Catastrophic* and PC is *Reasonably unlikely* THEN RM is *High*
Rule #148:	IF PO is *Very likely* and SC is *Catastrophic* and PC is *Likely* THEN RM is *Unacceptable*
Rule #149:	IF PO is *Very likely* and SC is *Catastrophic* and PC is *Reasonably likely* THEN RM is *Unacceptable*
Rule #150:	IF PO is *Very likely* and SC is *Catastrophic* and PC is *Highly likely* THEN RM is *Unacceptable*

APPENDIX E.

RAW DATA OF EXPERTS' JUDGEMENTS

Raw data of experts' judgements

BUILDING CONSTRUCTION PROJECT 1																
Evaluated by six experts																
Hazardous events	*Experts*	*Probability of occurrence*					*Severity of consequence*					*Probability of consequence*				
		Score	Converted STFN				Score	Converted STFN				Score	Converted STFN			
FH-01 Working platform	*E1 (0.20)*	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3
	E2 (0.18)	2	2	2	2	2	1	1	1	1	1	3	3	3	3	3
	E3 (0.18)	3	3	3	3	3	5	5	5	5	5	5	5	5	5	5
	E4 (0.18)	1	1	1	1	1	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(1,2)	1	1	2	2	(3,4,5)	3	4	4	5	1	1	1	1	1
	E6 (0.10)	2	2	2	2	2	(1,2)	1	1	2	2	3	3	3	3	3
FH-02 Placement ladder	*E1 (0.20)*	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4
	E2 (0.18)	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3
	E3 (0.18)	4	4	4	4	4	5	5	5	5	5	5	5	5	5	5
	E4 (0.18)	1	1	1	1	1	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E6 (0.10)	1	1	1	1	1	(1,2)	1	1	2	2	3	3	3	3	3
FH-03 Erection of scaffolding	*E1 (0.20)*	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3
	E2 (0.18)	2	2	2	2	2	1	1	1	1	1	2	2	2	2	2
	E3 (0.18)	4	4	4	4	4	5	5	5	5	5	4	4	4	4	4
	E4 (0.18)	2	2	2	2	2	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(1,2)	1	1	2	2	1	1	1	1	1	1	1	1	1	1
	E6 (0.10)	2	2	2	2	2	(1,2)	1	1	2	2	(1,2)	1	1	2	2
FH-04 Climbing cranes	*E1 (0.20)*	2	2	2	2	2	5	5	5	5	5	3	3	3	3	3
	E2 (0.18)	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
	E3 (0.18)	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	E4 (0.18)	1	1	1	1	1	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(1,2)	1	1	2	2	(3,4,5)	3	4	4	5	1	1	1	1	1
	E6 (0.10)	1	1	1	1	1	2	2	2	2	2	(1,2)	1	1	2	2
FH-05 Temporary ladder	*E1 (0.20)*	2	2	2	2	2	3	3	3	3	3	4	4	4	4	4
	E2 (0.18)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E3 (0.18)	3	3	3	3	3	4	4	4	4	4	6	6	6	6	6
	E4 (0.18)	1	1	1	1	1	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(1,2)	1	1	2	2	1	1	1	1	1	1	1	1	1	1
	E6 (0.10)	1	1	1	1	1	(1,2)	1	1	2	2	(2,3)	2	2	3	3
FH-06 Hole in the ground	*E1 (0.20)*	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4
	E2 (0.18)	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
	E3 (0.18)	5	5	5	5	5	5	5	5	5	5	6	6	6	6	6
	E4 (0.18)	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(1,2)	1	1	2	2	(2,3)	2	2	3	3	1	1	1	1	1
	E6 (0.10)	2	2	2	2	2	2	2	2	2	2	(2,3)	2	2	3	3
FH-07 Working on height unprotected	*E1 (0.20)*	4	4	4	4	4	5	5	5	5	5	5	5	5	5	5
	E2 (0.18)	(4,5)	4	4	5	5	4	4	4	4	4	5	5	5	5	5
	E3 (0.18)	4	4	4	4	4	4	4	4	4	4	6	6	6	6	6
	E4 (0.18)	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	3	3	3	3	3
	E6 (0.10)	(3,4)	3	3	4	4	(4,5)	4	4	5	5	4	4	4	4	4
FH-08 Through opening evevator shaft	*E1 (0.20)*	3	3	3	3	3	5	5	5	5	5	5	5	5	5	5
	E2 (0.18)	2	2	2	2	2	1	1	1	1	1	3	3	3	3	3
	E3 (0.18)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	E4 (0.18)	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(4,5)	4	4	5	5	(4,5)	4	4	5	5	1	1	1	1	1
	E6 (0.10)	2	2	2	2	2	(1,2)	1	1	2	2	(2,3)	2	2	3	3
FO-09 Part of climbing cranes, scaffolds	*E1 (0.20)*	3	3	3	3	3	5	5	5	5	5	4	4	4	4	4
	E2 (0.18)	2	2	2	2	2	2	2	2	2	2	4	4	4	4	4
	E3 (0.18)	3	3	3	3	3	3	3	3	3	3	6	6	6	6	6
	E4 (0.18)	1	1	1	1	1	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(2,3)	2	2	3	3	(3,4)	3	3	4	4	1	1	1	1	1
	E6 (0.10)	2	2	2	2	2	(2,3)	2	2	3	3	(4,5)	4	4	5	5
FO-10 Operating, cleaning and clearing	*E1 (0.20)*	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3
	E2 (0.18)	3	3	3	3	3	2	2	2	2	2	3	3	3	3	3
	E3 (0.18)	3	3	3	3	3	4	4	4	4	4	6	6	6	6	6
	E4 (0.18)	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3

	E5 (0.16)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E6 (0.10)	3	3	3	3	3	(2,3)	2	2	3	3	(2,3)	2	2	3	3
FO-11 Blown by wind	*E1 (0.20)*	4	4	4	4	4	3	3	3	3	3	2	2	2	2	2
	E2 (0.18)	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3
	E3 (0.18)	4	4	4	4	4	4	4	4	4	4	5	5	5	5	5
	E4 (0.18)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	E5 (0.16)	1	1	1	1	1	(2,3)	2	2	3	3	2	2	2	2	2
	E6 (0.10)	2	2	2	2	2	(3,4)	3	3	4	4	(2,3)	2	2	3	3
FO-12 Handheld tools	*E1 (0.20)*	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4
	E2 (0.18)	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3
	E3 (0.18)	4	4	4	4	4	5	5	5	5	5	6	6	6	6	6
	E4 (0.18)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	E5 (0.16)	1	1	1	1	1	(1,2)	1	1	2	2	1	1	1	1	1
	E6 (0.10)	2	2	2	2	2	(3,4)	3	3	4	4	(3,4)	3	3	4	4
FO-13 Hopper and bucket	*E1 (0.20)*	4	4	4	4	4	5	5	5	5	5	4	4	4	4	4
	E2 (0.18)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
	E3 (0.18)	4	4	4	4	4	3	3	3	3	3	4	4	4	4	4
	E4 (0.18)	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(1,2)	1	1	2	2	(2,3)	2	2	3	3	1	1	1	1	1
	E6 (0.10)	1	1	1	1	1	(2,3)	2	2	3	3	(2,3)	2	2	3	3
FO-14 Stacked items	*E1 (0.20)*	3	3	3	3	3	2	2	2	2	2	3	3	3	3	3
	E2 (0.18)	2	2	2	2	2	1	1	1	1	1	3	3	3	3	3
	E3 (0.18)	5	5	5	5	5	5	5	5	5	5	6	6	6	6	6
	E4 (0.18)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
	E5 (0.16)	1	1	1	1	1	(2,3)	2	2	3	3	1	1	1	1	1
	E6 (0.10)	2	2	2	2	2	(1,2)	1	1	2	2	(2,3)	2	2	3	3
FO-15 Objects under pressure or tension	*E1 (0.20)*	4	4	4	4	4	3	3	3	3	3	33	3	3	3	3
	E2 (0.18)	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3
	E3 (0.18)	3	3	3	3	3	5	5	5	5	5	5	5	5	5	5
	E4 (0.18)	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(2,3,4)	2	3	3	4	(3,4,5)	3	4	4	5	2	2	2	2	2
	E6 (0.10)	(1,2)	1	1	2	2	(1,2)	1	1	2	2	(4,5)	4	4	5	5
MH-16 Hoists	*E1 (0.20)*	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3
	E2 (0.18)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E3 (0.18)	4	4	4	4	4	5	5	5	5	5	5	5	5	5	5
	E4 (0.18)	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1
	E6 (0.10)	(1,2)	1	1	2	2	1	1	1	1	1	(2,3)	2	2	3	3
MH-17 Mobile crane lifting	*E1 (0.20)*	4	4	4	4	4	5	5	5	5	5	3	3	3	3	3
	E2 (0.18)	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	E3 (0.18)	3	3	3	3	3	4	4	4	4	4	6	6	6	6	6
	E4 (0.18)	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(2,3,4)	2	3	3	4	(3,4,5)	3	4	4	5	3	3	3	3	3
	E6 (0.10)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	(2,3)	2	2	3	3
EQ-18 Heavy equipment	*E1 (0.20)*	4	4	4	4	4	5	5	5	5	5	4	4	4	4	4
	E2 (0.18)	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
	E3 (0.18)	5	5	5	5	5	4	4	4	4	4	6	6	6	6	6
	E4 (0.18)	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(2,3)	2	2	3	3	(3,4,5)	3	4	4	5	2	2	2	2	2
	E6 (0.10)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	(2,3)	2	2	3	3
EQ-19 Steel bar bending machine	*E1 (0.20)*	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	E2 (0.18)	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
	E3 (0.18)	4	4	4	4	4	3	3	3	3	3	6	6	6	6	6
	E4 (0.18)	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
	E5 (0.16)	(1,2)	1	1	2	2	(3,4)	3	3	4	4	2	2	2	2	2
	E6 (0.10)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	(3,4)	3	3	4	4
EQ-20 Vibrator machine	*E1 (0.20)*	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	E2 (0.18)	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
	E3 (0.18)	4	4	4	4	4	5	5	5	5	5	6	6	6	6	6
	E4 (0.18)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
	E5 (0.16)	1	1	1	1	1	(2,3)	2	2	3	3	1	1	1	1	1
	E6 (0.10)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	(3,4)	3	3	4	4
EL-21 Wires	*E1 (0.20)*	3	3	3	3	3	5	5	5	5	5	4	4	4	4	4
	E2 (0.18)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
	E3 (0.18)	4	4	4	4	4	4	4	4	4	4	5	5	5	5	5
	E4 (0.18)	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(2,3)	2	2	3	3	(3,4)	3	3	4	4	3	3	3	3	3

	E6 (0.10)	1	1	1	1	1	(2,3)	2	2	3	3	(2,3)	2	2	3	3
EL-22 Electrical work	*E1 (0.20)*	2	2	2	2	2	5	5	5	5	5	3	3	3	3	3
	E2 (0.18)	2	2	2	2	2	4	4	4	4	4	3	3	3	3	3
	E3 (0.18)	4	4	4	4	4	4	4	4	4	4	6	6	6	6	6
	E4 (0.18)	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(2,3)	2	2	3	3	(3,4)	3	3	4	4	3	3	3	3	3
	E6 (0.10)	2	2	2	2	2	(4,5)	4	4	5	5	(3,4)	3	3	4	4
EL-23 Overhead power lines	*E1 (0.20)*	2	2	2	2	2	5	5	5	5	5	3	3	3	3	3
	E2 (0.18)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
	E3 (0.18)	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
	E4 (0.18)	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(1,2)	1	1	2	2	(3,4)	3	3	4	4	3	3	3	3	3
	E6 (0.10)	1	1	1	1	1	(2,3)	2	2	3	3	(2,3)	2	2	3	3
EL-24 Arcing welding machine	*E1 (0.20)*	2	2	2	2	2	4	4	4	4	4	3	3	3	3	3
	E2 (0.18)	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3
	E3 (0.18)	5	5	5	5	5	5	5	5	5	5	6	6	6	6	6
	E4 (0.18)	3	3	3	3	3	2	2	2	2	2	3	3	3	3	3
	E5 (0.16)	2	2	2	2	2	(3,4)	3	3	4	4	1	1	1	1	1
	E6 (0.10)	2	2	2	2	2	(3,4)	3	3	4	4	(2,3)	2	2	3	3
ST-25 Tripping over building materials	*E1 (0.20)*	3	3	3	3	3	3	3	3	3	3	5	5	5	5	5
	E2 (0.18)	2	2	2	2	2	1	1	1	1	1	3	3	3	3	3
	E3 (0.18)	3	3	3	3	3	4	4	4	4	4	5	5	5	5	5
	E4 (0.18)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
	E5 (0.16)	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
	E6 (0.10)	(2,3)	2	2	3	3	(1,2)	1	1	2	2	(3,4)	3	3	4	4
ST-26 Slipping wet surfaces	*E1 (0.20)*	4	4	4	4	4	3	3	3	3	3	5	5	5	5	5
	E2 (0.18)	2	2	2	2	2	1	1	1	1	1	2	2	2	2	2
	E3 (0.18)	3	3	3	3	3	5	5	5	5	5	6	6	6	6	6
	E4 (0.18)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
	E5 (0.16)	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
	E6 (0.10)	(2,3)	2	2	3	3	1	1	1	1	1	(1,2)	1	1	2	2
ST-27 Trips caused by small change in level	*E1 (0.20)*	4	4	4	4	4	3	3	3	3	3	5	5	5	5	5
	E2 (0.18)	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	E3 (0.18)	4	4	4	4	4	5	5	5	5	5	6	6	6	6	6
	E4 (0.18)	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
	E5 (0.16)	1	1	1	1	1	2	2	2	2	2	1	1	1	1	1
	E6 (0.10)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	(2,3)	2	2	3	3
ST-28 Trips caused by water pipes, rebar	*E1 (0.20)*	4	4	4	4	4	3	3	3	3	3	(4,5)	4	4	5	5
	E2 (0.18)	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	E3 (0.18)	4	4	4	4	4	5	5	5	5	5	5	5	5	5	5
	E4 (0.18)	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
	E5 (0.16)	1	1	1	1	1	2	2	2	2	2	1	1	1	1	1
	E6 (0.10)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	(1,2)	1	1	2	2
ST-29 Walking around construction site	*E1 (0.20)*	3	3	3	3	3	3	3	3	3	3	(4,5)	4	4	5	5
	E2 (0.18)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E3 (0.18)	5	5	5	5	5	4	4	4	4	4	6	6	6	6	6
	E4 (0.18)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
	E5 (0.16)	1	1	1	1	1	2	2	2	2	2	1	1	1	1	1
	E6 (0.10)	1	1	1	1	1	1	1	1	1	1	(2,3)	2	2	3	3
TH-30 Collison with another vehicles	*E1 (0.20)*	2	2	2	2	2	3	3	3	3	3	2	2	2	2	2
	E2 (0.18)	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3
	E3 (0.18)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	E4 (0.18)	1	1	1	1	1	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	1	1	1	1	1	2	2	2	2	2	1	1	1	1	1
	E6 (0.10)	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3
TH-31 Collision with plant/people	*E1 (0.20)*	2	2	2	2	2	4	4	4	4	4	2	2	2	2	2
	E2 (0.18)	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3
	E3 (0.18)	5	5	5	5	5	4	4	4	4	4	6	6	6	6	6
	E4 (0.18)	1	1	1	1	1	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	1	1	1	1	1	2	2	2	2	2	1	1	1	1	1
	E6 (0.10)	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3
VO-32 Crane overturn	*E1 (0.20)*	2	2	2	2	2	5	5	5	5	5	3	3	3	3	3

	E2 (0.18)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E3 (0.18)	4	4	4	4	4	3	3	3	3	3	5	5	5	5	5
	E4 (0.18)	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	2	2	2	2	2	3	3	3	3	3	1	1	1	1	1
	E6 (0.10)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
VO-33 Mobile plant (Bobcats, Tractor)	*E1 (0.20)*	2	2	2	2	2	5	5	5	5	5	4	4	4	4	4
	E2 (0.18)	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
	E3 (0.18)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	E4 (0.18)	1	1	1	1	1	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	2	2	2	2	2	3	3	3	3	3	1	1	1	1	1
	E6 (0.10)	(1,2)	1	1	2	2	2	2	2	2	2	3	3	3	3	3
FE-34 Hot work	*E1 (0.20)*	4	4	4	4	4	5	5	5	5	5	4	4	4	4	4
	E2 (0.18)	2	2	2	2	2	3	3	3	3	3	2	2	2	2	2
	E3 (0.18)	5	5	5	5	5	4	4	4	4	4	5	5	5	5	5
	E4 (0.18)	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	1	1	1	1	1
	E6 (0.10)	2	2	2	2	2	(3,4)	3	3	4	4	2	2	2	2	2
FE-35 Working near flammables	*E1 (0.20)*	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E2 (0.18)	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	E3 (0.18)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	E4 (0.18)	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(3,4)	3	3	4	4	(3,4,5)	3	4	4	5	1	1	1	1	1
	E6 (0.10)	2	2	2	2	2	(1,2)	1	1	2	2	2	2	2	2	2
FE-36 Gas cylinder or hose leakage	*E1 (0.20)*	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E2 (0.18)	2	2	2	2	2	1	1	1	1	1	2	2	2	2	2
	E3 (0.18)	5	5	5	5	5	4	4	4	4	4	6	6	6	6	6
	E4 (0.18)	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(3,4)	3	3	4	4	(3,4,5)	3	4	4	5	3	3	3	3	3
	E6 (0.10)	2	2	2	2	2	1	1	1	1	1	2	2	2	2	2
FE-37 Fire extinguisher has been discharged	*E1 (0.20)*	2	2	2	2	2	5	5	5	5	5	4	4	4	4	4
	E2 (0.18)	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
	E3 (0.18)	4	4	4	4	4	5	5	5	5	5	6	6	6	6	6
	E4 (0.18)	3	3	3	3	3	2	2	2	2	2	3	3	3	3	3
	E5 (0.16)	(3,4)	3	3	4	4	(3,4,5)	3	4	4	5	2	2	2	2	2
	E6 (0.10)	2	2	2	2	2	(2,3)	2	2	3	3	3	3	3	3	3
ES-38 Solvents	*E1 (0.20)*	2	2	2	2	2	5	5	5	5	5	3	3	3	3	3
	E2 (0.18)	2	2	2	2	2	1	1	1	1	1	2	2	2	2	2
	E3 (0.18)	5	5	5	5	5	5	5	5	5	5	6	6	6	6	6
	E4 (0.18)	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3
	E5 (0.16)	1	1	1	1	1	2	2	2	2	2	1	1	1	1	1
	E6 (0.10)	(3,4)	3	3	4	4	(1,2)	1	1	2	2	2	2	2	2	2
ES-39 Cement dust	*E1 (0.20)*	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3
	E2 (0.18)	(3,4)	3	3	4	4	4	4	4	4	4	4	4	4	4	4
	E3 (0.18)	5	5	5	5	5	5	5	5	5	5	6	6	6	6	6
	E4 (0.18)	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3
	E5 (0.16)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E6 (0.10)	2	2	2	2	2	(4,5)	4	4	5	5	4	4	4	4	4
ES-40 Corrosive substances	*E1 (0.20)*	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3
	E2 (0.18)	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
	E3 (0.18)	3	3	3	3	3	5	5	5	5	5	5	5	5	5	5
	E4 (0.18)	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3
	E5 (0.16)	1	1	1	1	1	2	2	2	2	2	1	1	1	1	1
	E6 (0.10)	2	2	2	2	2	(3,4)	3	3	4	4	3	3	3	3	3
CO-41 Collapse of boom(Cranes)	*E1 (0.20)*	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E2 (0.18)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E3 (0.18)	4	4	4	4	4	5	5	5	5	5	4	4	4	4	4
	E4 (0.18)	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	1	1	1	1	1	(3,4,5)	3	4	4	5	1	1	1	1	1
	E6 (0.10)	(1,2)	1	1	2	2	2	2	2	2	2	2	2	2	2	2
CO-42 Collapse of scaffolding	*E1 (0.20)*	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E2 (0.18)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E3 (0.18)	5	5	5	5	5	4	4	4	4	4	6	6	6	6	6
	E4 (0.18)	1	1	1	1	1	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(1,2)	1	1	2	2	(3,4,5)	3	4	4	5	1	1	1	1	1

	E6 (0.10)	(1,2)	1	1	2	2	1	1	1	1	1	2	2	2	2	2
CO-43 Temporary structure	*E1 (0.20)*	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E2 (0.18)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E3 (0.18)	3	3	3	3	3	4	4	4	4	4	5	5	5	5	5
	E4 (0.18)	1	1	1	1	1	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(2,3)	2	2	3	3	(3,4,5)	3	4	4	5	1	1	1	1	1
	E6 (0.10)	(1,2)	1	1	2	2	(1,2)	1	1	2	2	2	2	2	2	2
CO-44 Steel sheet piles	*E1 (0.20)*	2	2	2	2	2	5	5	5	5	5	3	3	3	3	3
	E2 (0.18)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
	E3 (0.18)	5	5	5	5	5	4	4	4	4	4	5	5	5	5	5
	E4 (0.18)	1	1	1	1	1	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(2,3,4)	2	3	3	4	(3,4,5)	3	4	4	5	1	1	1	1	1
	E6 (0.10)	(1,2)	1	1	2	2	(1,2)	1	1	2	2	4	4	4	4	4
CO-45 Kingpost	*E1 (0.20)*	2	2	2	2	2	5	5	5	5	5	3	3	3	3	3
	E2 (0.18)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
	E3 (0.18)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	E4 (0.18)	1	1	1	1	1	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(2,3)	2	2	3	3	(3,4,5)	3	4	4	5	1	1	1	1	1
	E6 (0.10)	(1,2)	1	1	2	2	(1,2)	1	1	2	2	4	4	4	4	4
CS-46 Deep excavations	*E1 (0.20)*	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E2 (0.18)	2	2	2	2	2	1	1	1	1	1	3	3	3	3	3
	E3 (0.18)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	E4 (0.18)	1	1	1	1	1	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(2,3,4)	2	3	3	4	(3,4,5)	3	4	4	5	1	1	1	1	1
	E6 (0.10)	(2,3)	2	2	3	3	1	1	1	1	1	4	4	4	4	4
CS-47 Closed tanks	*E1 (0.20)*	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E2 (0.18)	3	3	3	3	3	2	2	2	2	2	3	3	3	3	3
	E3 (0.18)	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	E4 (0.18)	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
	E5 (0.16)	(4,5)	4	4	5	5	(3,4,5)	3	4	4	5	1	1	1	1	1
	E6 (0.10)	(3,4)	3	3	4	4	2	2	2	2	2	4	4	4	4	4
EH-48 Poor work posture	*E1 (0.20)*	4	4	4	4	4	3	3	3	3	3	4	4	4	4	4
	E2 (0.18)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
	E3 (0.18)	4	4	4	4	4	3	3	3	3	3	6	6	6	6	6
	E4 (0.18)	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	(1,2)	1	1	2	2	(2,3)	2	2	3	3	1	1	1	1	1
	E6 (0.10)	(1,2)	1	1	2	2	(2,3)	2	2	3	3	(2,3)	2	2	3	3
EH-49 Repetitive movement	*E1 (0.20)*	4	4	4	4	4	2	2	2	2	2	4	4	4	4	4
	E2 (0.18)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
	E3 (0.18)	5	5	5	5	5	4	4	4	4	4	6	6	6	6	6
	E4 (0.18)	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1
	E6 (0.10)	(1,2)	1	1	2	2	(1,2)	1	1	2	2	(2,3)	2	2	3	3
EH-50 Extreme muscular exertion	*E1 (0.20)*	4	4	4	4	4	2	2	2	2	2	4	4	4	4	4
	E2 (0.18)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
	E3 (0.18)	4	4	4	4	4	5	5	5	5	5	6	6	6	6	6
	E4 (0.18)	3	3	3	3	3	5	5	5	5	5	3	3	3	3	3
	E5 (0.16)	2	2	2	2	2	(2,3,4)	2	3	3	4	1	1	1	1	1
	E6 (0.10)	(1,2)	1	1	2	2	(1,2)	1	1	2	2	(3,4)	3	3	4	4
NV-51 Piling	*E1 (0.20)*	3	3	3	3	3	(2,3)	2	2	3	3	5	5	5	5	5
	E2 (0.18)	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4
	E3 (0.18)	4	4	4	4	4	5	5	5	5	5	5	5	5	5	5
	E4 (0.18)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	E5 (0.16)	2	2	2	2	2	(2,3,4)	2	3	3	4	3	3	3	3	3
	E6 (0.10)	(3,4)	3	3	4	4	3	3	3	3	3	(4,5)	4	4	5	5
NV-52 Excavation	*E1 (0.20)*	3	3	3	3	3	(2,3)	2	2	3	3	5	5	5	5	5
	E2 (0.18)	2	2	2	2	2	2	2	2	2	2	4	4	4	4	4
	E3 (0.18)	4	4	4	4	4	5	5	5	5	5	4	4	4	4	4
	E4 (0.18)	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3
	E5 (0.16)	(2,3)	2	2	3	3	(2,3,4)	2	3	3	4	3	3	3	3	3
	E6 (0.10)	(2,3)	2	2	3	3	(1,2)	1	1	2	2	(3,4)	3	3	4	4
NV-53 Hammering	*E1 (0.20)*	3	3	3	3	3	(2,3)	2	2	3	3	5	5	5	5	5
	E2 (0.18)	3	3	3	3	3	4	4	4	4	4	5	5	5	5	5
	E3 (0.18)	5	5	5	5	5	4	4	4	4	4	6	6	6	6	6
	E4 (0.18)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	E5 (0.16)	(2,3,4)	2	3	3	4	(2,3,4)	2	3	3	4	3	3	3	3	3
	E6 (0.10)	(3,4)	3	3	4	4	(2,3)	2	2	3	3	(5,6)	5	5	6	6

NV-54 Vibrator machine	*E1 (0.20)*	3	3	3	3	3	(2,3)	2	2	3	3	4	4	4	4	4
	E2 (0.18)	3	3	3	3	3	4	4	4	4	4	5	5	5	5	5
	E3 (0.18)	4	4	4	4	4	4	4	4	4	4	5	5	5	5	5
	E4 (0.18)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
	E5 (0.16)	1	1	1	1	1	2	2	2	2	2	1	1	1	1	1
	E6 (0.10)	(3,4)	3	3	4	4	(3,4)	3	3	4	4	(5,6)	5	5	6	6
NV-55 Hand-held power tools	*E1 (0.20)*	2	2	2	2	2	(2,3)	2	2	3	3	3	3	3	3	3
	E2 (0.18)	1	1	1	1	1	2	2	2	2	2	4	4	4	4	4
	E3 (0.18)	4	4	4	4	4	5	5	5	5	5	6	6	6	6	6
	E4 (0.18)	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3
	E5 (0.16)	1	1	1	1	1	(2,3)	2	2	3	3	1	1	1	1	1
	E6 (0.10)	(1,2)	1	1	2	2	(1,2)	1	1	2	2	(3,4)	3	3	4	4

Comparison by expert judgements of hazard groups in building construction project 1

Comparison	E_1(0.20)					E_2(0.18)					E_3(0.18)					E_4(0.18)				
	Score	Converted STFN				Score	Converted STFN				Score	Converted STFN				Score	Converted STFN			
WH vs FO (RH_{12})	(3,4,5)	3.00	4.00	4.00	5.00	0.33	0.33	0.33	0.33	0.33	2	2.00	2.00	2.00	2.00	1	1.00	1.00	1.00	1.00
FO vs MH (RH_{23})	1	1.00	1.00	1.00	1.00	2	2.00	2.00	2.00	2.00	1	1.00	1.00	1.00	1.00	1	1.00	1.00	1.00	1.00
MH vs EQ (RH_{34})	(3,4,5)	3.00	4.00	4.00	5.00	4	4.00	4.00	4.00	4.00	0.2	0.20	0.20	0.20	0.20	1	1.00	1.00	1.00	1.00
EQ vs EL (RH_{45})	1	1.00	1.00	1.00	1.00	2	2.00	2.00	2.00	2.00	3	3.00	3.00	3.00	3.00	0.2	0.20	0.20	0.20	0.20
EL vs ST (RH_{56})	(3,4,5)	3.00	4.00	4.00	5.00	1	1.00	1.00	1.00	1.00	0.25	0.25	0.25	0.25	0.25	9	9.00	9.00	9.00	9.00
ST vs TH (RH_{67})	(4,5)	4.00	4.00	5.00	5.00	0.5	0.50	0.50	0.50	0.50	0.33	0.33	0.33	0.33	0.33	0.11	0.11	0.11	0.11	0.11
TH vs VO (RH_{78})	(0.20, 0.25,0.33)	0.20	0.25	0.25	0.33	2	2.00	2.00	2.00	2.00	0.33	0.33	0.33	0.33	0.33	0.11	0.11	0.11	0.11	0.11
VO vs FE (RH_{89})	(3,4,5)	3.00	4.00	4.00	5.00	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.11	0.11	0.11	0.11	0.11
EF vs ES ($RH_{9,10}$)	(3,4,5)	3.00	4.00	4.00	5.00	3	3.00	3.00	3.00	3.00	3	3.00	3.00	3.00	3.00	9	9.00	9.00	9.00	9.00
ES vs CO ($RH_{10,11}$)	(0.14, 0.17,0.20)	0.14	0.17	0.17	0.20	4	4.00	4.00	4.00	4.00	2	2.00	2.00	2.00	2.00	0.11	0.11	0.11	0.11	0.11
CO vs CS ($RH_{11,12}$)	1	1.00	1.00	1.00	1.00	0.33	0.33	0.33	0.33	0.33	0.14	0.14	0.14	0.14	0.14	9	9.00	9.00	9.00	9.00
CS vs EH ($RH_{12,13}$)	7	7.00	7.00	7.00	7.00	3	3.00	3.00	3.00	3.00	3	3.00	3.00	3.00	3.00	0.11	0.11	0.11	0.11	0.11
EH vs NV ($RH_{13,14}$)	1	1.00	1.00	1.00	1.00	2	2.00	2.00	2.00	2.00	0.25	0.25	0.25	0.25	0.25	9	9.00	9.00	9.00	9.00

Comparison	E_5(0.16)					E_6(0.10)				
	Score	Converted STFN				Score	Converted STFN			
WH vs FO (RH_{12})	(2,3,4)	2.00	3.00	3.00	4	(0.33,0.5)	0.33	0.33	0.50	0.50
FO vs MH (RH_{23})	(0.14,0.17.0.20)	0.14	0.17	0.17	0.20	(1,2)	1.00	1.00	2.00	2.00
MH vs EQ (RH_{34})	(0.11, 0.13,0.14)	0.11	0.13	0.13	0.14	(4,5)	4.00	4.00	5.00	5.00
EQ vs EL (RH_{45})	(7,8,9)	7.00	8.00	8.00	9.00	(1,2)	1.00	1.00	2.00	2.00
EL vs ST (RH_{56})	(7,8,9)	7.00	8.00	8.00	9.00	(0.5,1)	0.50	0.50	1.00	1.00
ST vs TH (RH_{67})	(4,5,6)	4.00	5.00	5.00	6.00	(0.11,0.13,0.14)	0.11	0.13	0.13	0.14
TH vs VO (RH_{78})	1	1.00	1.00	1.00	1.00	2	2.00	2.00	2.00	2.00
VO vs FE (RH_{89})	(0.14,0.17,0.20)	0.14	0.17	0.17	0.20	(0.11,0.13,0.14)	0.11	0.13	0.13	0.14
EF vs ES ($RH_{9,10}$)	(2,3)	2.00	2.00	3.00	3.00	(3,4)	3.00	3.00	4.00	4.00
ES vs CO ($RH_{10,11}$)	(0.11,0.13,0.14)	0.11	0.13	0.13	0.14	(3,4)	3.00	3.00	4.00	4.00
CO vs CS ($RH_{11,12}$)	(7,8,9)	7.00	8.00	8.00	9.00	(0.33,0.5)	0.33	0.33	0.50	0.50
CS vs EH ($RH_{12,13}$)	(7,8,9)	7.00	8.00	8.00	9.00	(3,4)	3.00	3.00	4.00	4.00
EH vs NV ($RH_{13,14}$)	(0.14, 0.13, 0.11)	0.14	0.13	0.13	0.11	(1,2)	1.00	1.00	2.00	2.00

BUILDING CONSTRUCTION PROJECT 2																
Evaluated by five experts																
Hazardous events	*Experts*	*Probability of occurrence*					*Severity of consequence*					*Probability of consequence*				
		Score	Converted STFN				Score	Converted STFN				Score	Converted STFN			
FH-01 Working platform	*E1 (0.25)*	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
	E2 (0.25)	1	1	1	1	1	(4,5)	4	4	5	5	3	3	3	3	3
	E3 (0.25)	1	1	1	1	1	(2,3)	2	2	3	3	2	2	2	2	2
	E4 (0.125)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
	E5 (0.125)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
FH-02 Erection of scaffolding	*E1 (0.25)*	1	1	1	1	1	2	2	2	2	2	(3,4)	3	3	4	4
	E2 (0.25)	1	1	1	1	1	(2,3)	2	2	3	3	3	3	3	3	3
	E3 (0.25)	1	1	1	1	1	(2,3)	2	2	3	3	2	2	2	2	2
	E4 (0.125)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
	E5 (0.125)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
FH-03 Climbing cranes	*E1 (0.25)*	1	1	1	1	1	5	5	5	5	5	2	2	2	2	2
	E2 (0.25)	1	1	1	1	1	4	4	4	4	4	2	2	2	2	2
	E3 (0.25)	1	1	1	1	1	3	3	3	3	3	1	1	1	1	1
	E4 (0.125)	1	1	1	1	1	4	4	4	4	4	2	2	2	2	2
	E5 (0.125)	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
FH-04 Temporary ladder	*E1 (0.25)*	1	1	1	1	1	5	5	5	5	5	2	2	2	2	2
	E2 (0.25)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
	E3 (0.25)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
	E4 (0.125)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
	E5 (0.125)	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
FH-05 Hole in the ground	*E1 (0.25)*	1	1	1	1	1	5	5	5	5	5	(3,4)	3	3	4	4
	E2 (0.25)	2	2	2	2	2	(2,3)	2	2	3	3	5	5	5	5	5
	E3 (0.25)	1	1	1	1	1	3	3	3	3	3	1	1	1	1	1
	E4 (0.125)	1	1	1	1	1	5	5	5	5	5	2	2	2	2	2
	E5 (0.125)	1	1	1	1	1	3	3	3	3	3	4	4	4	4	4
FH-06 Working on height unprotected	*E1 (0.25)*	5	5	5	5	5	5	5	5	5	5	(3,4)	3	3	4	4
	E2 (0.25)	1	1	1	1	1	2	2	2	2	2	4	4	4	4	4
	E3 (0.25)	2	2	2	2	2	(3,4)	3	3	4	4	2	2	2	2	2
	E4 (0.125)	2	2	2	2	2	2	2	2	2	2	4	4	4	4	4
	E5 (0.125)	1	1	1	1	1	3	3	3	3	3	4	4	4	4	4
FH-07 Through opening elevator shaft	*E1 (0.25)*	1	1	1	1	1	5	5	5	5	5	2	2	2	2	2
	E2 (0.25)	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3
	E3 (0.25)	1	1	1	1	1	(2,3)	2	2	3	3	(1,2)	1	1	2	2
	E4 (0.125)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
	E5 (0.125)	1	1	1	1	1	5	5	5	5	5	3	3	3	3	3
FH-08 Working formwork	*E1 (0.25)*	1	1	1	1	1	5	5	5	5	5	(3,4)	3	3	4	4
	E2 (0.25)	1	1	1	1	1	2	2	2	2	2	4	4	4	4	4
	E3 (0.25)	1	1	1	1	1	2	2	2	2	2	1	1	1	1	1
	E4 (0.125)	1	1	1	1	1	3	3	3	3	3	1	1	1	1	1
	E5 (0.125)	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3
FH-09 Excavation hole	*E1 (0.25)*	1	1	1	1	1	5	5	5	5	5	2	2	2	2	2
	E2 (0.25)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
	E3 (0.25)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
	E4 (0.125)	1	1	1	1	1	4	4	4	4	4	1	1	1	1	1
	E5 (0.125)	2	2	2	2	2	3	3	3	3	3	2	2	2	2	2
FO-10 Part of climbing cranes, scaffolds	*E1 (0.25)*	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
	E2 (0.25)	3	3	3	3	3	(3,4,5)	3	4	4	5	4	4	4	4	4
	E3 (0.25)	1	1	1	1	1	(3,4)	3	3	4	4	2	2	2	2	2
	E4 (0.125)	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
	E5 (0.125)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
FO-11 Operating, cleaning and clearing	*E1 (0.25)*	2	2	2	2	2	3	3	3	3	3	2	2	2	2	2
	E2 (0.25)	3	3	3	3	3	(3,4,5)	3	4	4	5	4	4	4	4	4
	E3 (0.25)	2	2	2	2	2	2	2	2	2	2	1	1	1	1	1
	E4 (0.125)	4	4	4	4	4	3	3	3	3	3	6	6	6	6	6
	E5 (0.125)	(3,4)	3	3	4	4	3	3	3	3	3	3	3	3	3	3
FO-12 Handheld tools	*E1 (0.25)*	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	E2 (0.25)	2	2	2	2	2	(2,3)	2	2	3	3	5	5	5	5	5
	E3 (0.25)	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
	E4 (0.125)	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
	E5 (0.125)	(3,4)	3	3	4	4	3	3	3	3	3	3	3	3	3	3

FO-13 Post-Tension	*E1 (0.25)*	1	1	1	1	1	5	5	5	5	5	1	1	1	1	1
	E2 (0.25)	1	1	1	1	1	(4,5)	4	4	5	5	3	3	3	3	3
	E3 (0.25)	1	1	1	1	1	(4,5)	4	4	5	5	2	2	2	2	2
	E4 (0.125)	1	1	1	1	1	2	2	2	2	2	1	1	1	1	1
	E5 (0.125)	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
FO-14 Blown by wind	*E1 (0.25)*	1	1	1	1	1	2	2	2	2	2	1	1	1	1	1
	E2 (0.25)	4	4	4	4	4	2	2	2	2	2	5	5	5	5	5
	E3 (0.25)	2	2	2	2	2	3	3	3	3	3	1	1	1	1	1
	E4 (0.125)	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
	E5 (0.125)	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
MH-15 Hoists	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E2 (0.25)	3	3	3	3	3	2	2	2	2	2	3	3	3	3	3
	E3 (0.25)	1	1	1	1	1	(4,5)	4	4	5	5	2	2	2	2	2
	E4 (0.125)	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
	E5 (0.125)	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
MH-16 Poor rigging	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	(3,4)	3	3	4	4
	E2 (0.25)	3	3	3	3	3	2	2	2	2	2	4	4	4	4	4
	E3 (0.25)	1	1	1	1	1	3	3	3	3	3	1	1	1	1	1
	E4 (0.125)	2	2	2	2	2	1	1	1	1	1	3	3	3	3	3
	E5 (0.125)	2	2	2	2	2	3	3	3	3	3	2	2	2	2	2
MH-17 Mobile crane lifting	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	(3,4)	3	3	4	4
	E2 (0.25)	3	3	3	3	3	2	2	2	2	2	3	3	3	3	3
	E3 (0.25)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
	E4 (0.125)	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3
	E5 (0.125)	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
EQ-18 Cutting machine	*E1 (0.25)*	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
	E2 (0.25)	2	2	2	2	2	(2,3)	2	2	3	3	4	4	4	4	4
	E3 (0.25)	1	1	1	1	1	(3,4)	3	3	4	4	1	1	1	1	1
	E4 (0.125)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E5 (0.125)	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
EQ-19 Steel bar bending machine	*E1 (0.25)*	1	1	1	1	1	3	3	3	3	3	(3,4)	3	3	4	4
	E2 (0.25)	3	3	3	3	3	2	2	2	2	2	4	4	4	4	4
	E3 (0.25)	1	1	1	1	1	(3,4)	3	3	4	4	1	1	1	1	1
	E4 (0.125)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E5 (0.125)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
EQ-20 Grinder machine	*E1 (0.25)*	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
	E2 (0.25)	4	4	4	4	4	(2,3)	2	2	3	3	5	5	5	5	5
	E3 (0.25)	1	1	1	1	1	(4,5)	4	4	5	5	2	2	2	2	2
	E4 (0.125)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
	E5 (0.125)	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3
EQ-21 Welding machine	*E1 (0.25)*	1	1	1	1	1	2	2	2	2	2	1	1	1	1	1
	E2 (0.25)	4	4	4	4	4	2	2	2	2	2	4	4	4	4	4
	E3 (0.25)	1	1	1	1	1	(4,5)	4	4	5	5	2	2	2	2	2
	E4 (0.125)	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	E5 (0.125)	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
EQ-22 Concrete breaking machine	*E1 (0.25)*	1	1	1	1	1	2	2	2	2	2	1	1	1	1	1
	E2 (0.25)	4	4	4	4	4	2	2	2	2	2	5	5	5	5	5
	E3 (0.25)	1	1	1	1	1	(3,4)	3	3	4	4	2	2	2	2	2
	E4 (0.125)	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
	E5 (0.125)	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
EL-23 Wires	*E1 (0.25)*	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
	E2 (0.25)	3	3	3	3	3	2	2	2	2	2	4	4	4	4	4
	E3 (0.25)	2	2	2	2	2	(3,4)	3	3	4	4	1	1	1	1	1
	E4 (0.125)	2	2	2	2	2	2	2	2	2	2	4	4	4	4	4
	E5 (0.125)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
EL-24 Electrical work	*E1 (0.25)*	1	1	1	1	1	3	3	3	3	3	(3,4)	3	3	4	4
	E2 (0.25)	4	4	4	4	4	1	1	1	1	1	4	4	4	4	4
	E3 (0.25)	1	1	1	1	1	4	4	4	4	4	1	1	1	1	1
	E4 (0.125)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E5 (0.125)	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3
EL-25 Overhead power lines	*E1 (0.25)*	1	1	1	1	1	3	3	3	3	3	1	1	1	1	1
	E2 (0.25)	3	3	3	3	3	1	1	1	1	1	3	3	3	3	3
	E3 (0.25)	1	1	1	1	1	3	3	3	3	3	1	1	1	1	1
	E4 (0.125)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E5 (0.125)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
EL-26 Arcing welding machine	*E1 (0.25)*	1	1	1	1	1	3	3	3	3	3	1	1	1	1	1

	E2 (0.25)	4	4	4	4	4	2	2	2	2	2	4	4	4	4	4
	E3 (0.25)	2	2	2	2	2	3	3	3	3	3	1	1	1	1	1
	E4 (0.125)	2	2	2	2	2	2	2	2	2	2	4	4	4	4	4
	E5 (0.125)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
ST-27 Tripping over building materials	*E1 (0.25)*	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
	E2 (0.25)	4	4	4	4	4	1	1	1	1	1	5	5	5	5	5
	E3 (0.25)	1	1	1	1	1	(2,3)	2	2	3	3	2	2	2	2	2
	E4 (0.125)	2	2	2	2	2	2	2	2	2	2	5	5	5	5	5
	E5 (0.125)	4	4	4	4	4	2	2	2	2	2	4	4	4	4	4
ST-28 Slipping wet surfaces	*E1 (0.25)*	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
	E2 (0.25)	4	4	4	4	4	2	2	2	2	2	5	5	5	5	5
	E3 (0.25)	1	1	1	1	1	(3,4)	3	3	4	4	2	2	2	2	2
	E4 (0.125)	1	1	1	1	1	2	2	2	2	2	5	5	5	5	5
	E5 (0.125)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
ST-29 Trips caused by small change in level	*E1 (0.25)*	1	1	1	1	1	2	2	2	2	2	(3,4)	3	3	4	4
	E2 (0.25)	4	4	4	4	4	1	1	1	1	1	6	6	6	6	6
	E3 (0.25)	1	1	1	1	1	4	4	4	4	4	(1,2)	1	1	2	2
	E4 (0.125)	2	2	2	2	2	1	1	1	1	1	5	5	5	5	5
	E5 (0.125)	4	4	4	4	4	2	2	2	2	2	4	4	4	4	4
ST-30 Trips caused by water pipes, rebar	*E1 (0.25)*	1	1	1	1	1	2	2	2	2	2	(3,4)	3	3	4	4
	E2 (0.25)	4	4	4	4	4	2	2	2	2	2	6	6	6	6	6
	E3 (0.25)	1	1	1	1	1	2	2	2	2	2	1	1	1	1	1
	E4 (0.125)	1	1	1	1	1	1	1	1	1	1	5	5	5	5	5
	E5 (0.125)	4	4	4	4	4	2	2	2	2	2	4	4	4	4	4
TH-31 Collison with another vehicles	*E1 (0.25)*	2	2	2	2	2	1	1	1	1	1	(3,4)	3	3	4	4
	E2 (0.25)	4	4	4	4	4	1	1	1	1	1	4	4	4	4	4
	E3 (0.25)	1	1	1	1	1	4	4	4	4	4	2	2	2	2	2
	E4 (0.125)	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	E5 (0.125)	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
TH-32 Collision with plant/people	*E1 (0.25)*	2	2	2	2	2	2	2	2	2	2	(3,4)	3	3	4	4
	E2 (0.25)	4	4	4	4	4	2	2	2	2	2	4	4	4	4	4
	E3 (0.25)	1	1	1	1	1	4	4	4	4	4	2	2	2	2	2
	E4 (0.125)	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
	E5 (0.125)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
FE-33 Hot work	*E1 (0.25)*	3	3	3	3	3	3	3	3	3	3	2	2	2	2	2
	E2 (0.25)	5	5	5	5	5	1	1	1	1	1	6	6	6	6	6
	E3 (0.25)	2	2	2	2	2	(4,5)	4	4	5	5	1	1	1	1	1
	E4 (0.125)	2	2	2	2	2	2	2	2	2	2	5	5	5	5	5
	E5 (0.125)	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
FE-34 Working near flammables	*E1 (0.25)*	3	3	3	3	3	3	3	3	3	3	2	2	2	2	2
	E2 (0.25)	3	3	3	3	3	2	2	2	2	2	4	4	4	4	4
	E3 (0.25)	2	2	2	2	2	(3,4)	3	3	4	4	2	2	2	2	2
	E4 (0.125)	2	2	2	2	2	3	3	3	3	3	5	5	5	5	5
	E5 (0.125)	1	1	1	1	1	4	4	4	4	4	4	4	4	4	4
FE-35 Gas cylinder or hose leakage	*E1 (0.25)*	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3
	E2 (0.25)	4	4	4	4	4	1	1	1	1	1	3	3	3	3	3
	E3 (0.25)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
	E4 (0.125)	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3
	E5 (0.125)	3	3	3	3	3	2	2	2	2	2	4	4	4	4	4
FE-36 Fire extinguisher has been discharged	*E1 (0.25)*	5	5	5	5	5	3	3	3	3	3	3	3	3	3	3
	E2 (0.25)	4	4	4	4	4	1	1	1	1	1	3	3	3	3	3
	E3 (0.25)	1	1	1	1	1	4	4	4	4	4	1	1	1	1	1
	E4 (0.125)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E5 (0.125)	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
ES-37 Cement dust	*E1 (0.25)*	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
	E2 (0.25)	5	5	5	5	5	2	2	2	2	2	6	6	6	6	6
	E3 (0.25)	2	2	2	2	2	3	3	3	3	3	2	2	2	2	2
	E4 (0.125)	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3
	E5 (0.125)	2	2	2	2	2	1	1	1	1	1	3	3	3	3	3
ES-38 Formwork striking oil, epoxy	*E1 (0.25)*	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3

	E2 (0.25)	3	3	3	3	3	1	1	1	1	1	4	4	4	4	4
	E3 (0.25)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
	E4 (0.125)	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3
	E5 (0.125)	2	2	2	2	2	1	1	1	1	1	3	3	3	3	3
CO-39 Temporary structure	*E1 (0.25)*	1	1	1	1	1	5	5	5	5	5	1	1	1	1	1
	E2 (0.25)	1	1	1	1	1	(3,4)	3	3	4	4	2	2	2	2	2
	E3 (0.25)	2	2	2	2	2	(4,5)	4	4	5	5	1	1	1	1	1
	E4 (0.125)	1	1	1	1	1	3	3	3	3	3	3	3	3	3	3
	E5 (0.125)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
CO-40 Collapse of scaffolding	*E1 (0.25)*	1	1	1	1	1	5	5	5	5	5	1	1	1	1	1
	E2 (0.25)	1	1	1	1	1	(3,4,5)	3	4	4	5	22	2	2	2	2
	E3 (0.25)	1	1	1	1	1	(3,4)	3	3	4	4	1	1	1	1	1
	E4 (0.125)	2	2	2	2	2	3	3	3	3	3	4	4	4	4	4
	E5 (0.125)	1	1	1	1	1	4	4	4	4	4	2	2	2	2	2
CO-41 Steel sheet piles	*E1 (0.25)*	1	1	1	1	1	5	5	5	5	5	1	1	1	1	1
	E2 (0.25)	1	1	1	1	1	(3,4,5)	3	4	4	5	1	1	1	1	1
	E3 (0.25)	1	1	1	1	1	(4,5)	4	4	5	5	1	1	1	1	1
	E4 (0.125)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
	E5 (0.125)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
CO-42 Kingpost	*E1 (0.25)*	1	1	1	1	1	5	5	5	5	5	1	1	1	1	1
	E2 (0.25)	1	1	1	1	1	(3,4,5)	3	4	4	5	1	1	1	1	1
	E3 (0.25)	1	1	1	1	1	(4,5)	4	4	5	5	1	1	1	1	1
	E4 (0.125)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
	E5 (0.125)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
CS-43 Deep excavations	*E1 (0.25)*	1	1	1	1	1	5	5	5	5	5	1	1	1	1	1
	E2 (0.25)	1	1	1	1	1	(3,4,5)	3	4	4	5	3	3	3	3	3
	E3 (0.25)	2	2	2	2	2	(3,4)	3	3	4	4	2	2	2	2	2
	E4 (0.125)	1	1	1	1	1	3	3	3	3	3	1	1	1	1	1
	E5 (0.125)	1	1	1	1	1	5	5	5	5	5	3	3	3	3	3
CS-44 Closed tanks	*E1 (0.25)*	1	1	1	1	1	5	5	5	5	5	1	1	1	1	1
	E2 (0.25)	1	1	1	1	1	(3,4,5)	3	4	4	5	2	2	2	2	2
	E3 (0.25)	1	1	1	1	1	4	4	4	4	4	2	2	2	2	2
	E4 (0.125)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E5 (0.125)	1	1	1	1	1	5	5	5	5	5	3	3	3	3	3
EH-45 Poor work posture	*E1 (0.25)*	1	1	1	1	1	3	3	3	3	3	(3,4)	3	3	4	4
	E2 (0.25)	4	4	4	4	4	2	2	2	2	2	6	6	6	6	6
	E3 (0.25)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
	E4 (0.125)	2	2	2	2	2	2	2	2	2	2	5	5	5	5	5
	E5 (0.125)	3	3	3	3	3	2	2	2	2	2	3	3	3	3	3
EH-46 Extreme muscular exertion	*E1 (0.25)*	1	1	1	1	1	3	3	3	3	3	(3,4)	3	3	4	4
	E2 (0.25)	4	4	4	4	4	(2,3)	2	2	3	3	5	5	5	5	5
	E3 (0.25)	2	2	2	2	2	3	3	3	3	3	(2,3)	2	2	3	3
	E4 (0.125)	2	2	2	2	2	2	2	2	2	2	5	5	5	5	5
	E5 (0.125)	3	3	3	3	3	2	2	2	2	2	3	3	3	3	3
NV-47 Piling	*E1 (0.25)*	1	1	1	1	1	3	3	3	3	3	1	1	1	1	1
	E2 (0.25)	2	2	2	2	2	1	1	1	1	1	3	3	3	3	3
	E3 (0.25)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
	E4 (0.125)	2	2	2	2	2	2	2	2	2	2	5	5	5	5	5
	E5 (0.125)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
NV-48 Excavation	*E1 (0.25)*	1	1	1	1	1	5	5	5	5	5	1	1	1	1	1
	E2 (0.25)	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3
	E3 (0.25)	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
	E4 (0.125)	2	2	2	2	2	2	2	2	2	2	5	5	5	5	5
	E5 (0.125)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
NV-49 Hammering	*E1 (0.25)*	1	1	1	1	1	5	5	5	5	5	1	1	1	1	1
	E2 (0.25)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
	E3 (0.25)	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
	E4 (0.125)	3	3	3	3	3	3	3	3	3	3	5	5	5	5	5
	E5 (0.125)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
NV-50 Vibrator machine	*E1 (0.25)*	1	1	1	1	1	3	3	3	3	3	1	1	1	1	1
	E2 (0.25)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E3 (0.25)	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
	E4 (0.125)	2	2	2	2	2	3	3	3	3	3	5	5	5	5	5
	E5 (0.125)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
NV-51 Hand-held power tools	*E1 (0.25)*	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2
	E2 (0.25)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2

	E3 (0.25)	1	1	1	1	1	2	2	2	2	2	(1,2)	1	1	2	2
	E4 (0.125)	2	2	2	2	2	2	2	2	2	2	5	5	5	5	5
	E5 (0.125)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
NV-52 Concrete pump machine	*E1 (0.25)*	1	1	1	1	1	3	3	3	3	3	(3,4)	3	3	4	4
	E2 (0.25)	3	3	3	3	3	2	2	2	2	2	4	4	4	4	4
	E3 (0.25)	2	2	2	2	2	3	3	3	3	3	2	2	2	2	2
	E4 (0.125)	2	2	2	2	2	2	2	2	2	2	5	5	5	5	5
	E5 (0.125)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Comparison by expert judgements of hazard groups in building construction project 2

Comparison	E_1 (0.25)					E_2 (0.25)					E_3 (0.25)					E_4 (0.125)				
	Score	Converted STFN				Score	Converted STFN				Score	Converted STFN				Score	Converted STFN			
FH vs FO (RH_{12})	1	1.00	1.00	1.00	1.00	5	5.00	5.00	5.00	5.00	9	9.00	9.00	9.00	9.00	1	1.00	1.00	1.00	1.00
FO vs MH (RH_{23})	8	8.00	8.00	8.00	8.00	5	5.00	5.00	5.00	5.00	7	7.00	7.00	7.00	7.00	7	7.00	7.00	7.00	7.00
MH vs EQ (RH_{34})	1	1.00	1.00	1.00	1.00	1/3	0.33	0.33	0.33	0.33	1/7	0.14	0.14	0.14	0.14	1/7	0.14	0.14	0.14	0.14
EQ vs EL (RH_{45})	1	1.00	1.00	1.00	1.00	3	3.00	3.00	3.00	3.00	1/9	0.11	0.11	0.11	0.11	1/4	0.25	0.25	0.25	0.25
EL vs ST (RH_{56})	8	8.00	8.00	8.00	8.00	5	5.00	5.00	5.00	5.00	9	9.00	9.00	9.00	9.00	7	7.00	7.00	7.00	7.00
ST vs TH (RH_{67})	1	1.00	1.00	1.00	1.00	1/5	0.20	0.20	0.20	0.20	7	7.00	7.00	7.00	7.00	4	4.00	4.00	4.00	4.00
TH vs FE (RH_{78})	1/9	0.11	0.11	0.11	0.11	1/5	0.20	0.20	0.20	0.20	1/9	0.11	0.11	0.11	0.11	1/8	0.13	0.13	0.13	0.13
FE vs ES ($RH_{8,9}$)	8	8.00	8.00	8.00	8.00	5	5.00	5.00	5.00	5.00	9	9.00	9.00	9.00	9.00	5	5.00	5.00	5.00	5.00
ES vs CO ($RH_{9,10}$)	1/9	0.11	0.11	0.11	0.11	1/7	0.14	0.14	0.14	0.14	7	7.00	7.00	7.00	7.00	1/5	0.20	0.20	0.20	0.20
CO vs CS ($RH_{10,11}$)	1	1.00	1.00	1.00	1.00	1/5	0.20	0.20	0.20	0.20	1	1.00	1.00	1.00	1.00	1	1.00	1.00	1.00	1.00
CS vs EH ($RH_{11,12}$)	9	9.00	9.00	9.00	9.00	5	5.00	5.00	5.00	5.00	9	9.00	9.00	9.00	9.00	6	6.00	6.00	6.00	6.00
EH vs NV ($RH_{12,13}$)	1/8	0.13	0.13	0.13	0.13	3	3.00	3.00	3.00	3.00	6	6.00	6.00	6.00	6.00	1	1.00	1.00	1.00	1.00

Comparison	E_5 (0.125)				
	Score	Converted STFN			
FH vs FO (RH_{12})	1	1.00	1.00	1.00	1.00
FO vs MH (RH_{23})	7	7.00	7.00	7.00	7.00
MH vs EQ (RH_{34})	1/7	0.14	0.14	0.14	0.14
EQ vs EL (RH_{45})	1/7	0.14	0.14	0.14	0.14
EL vs ST (RH_{56})	1/7	0.14	0.14	0.14	0.14
ST vs TH (RH_{67})	1/5	0.20	0.20	0.20	0.20
TH vs FE (RH_{78})	1/9	0.11	0.11	0.11	0.11
FE vs ES ($RH_{8,9}$)	9	9.00	9.00	9.00	9.00
ES vs CO ($RH_{9,10}$)	1/5	0.20	0.20	0.20	0.20
CO vs CS ($RH_{10,11}$)	1	1.00	1.00	1.00	1.00
CS vs EH ($RH_{11,12}$)	9	9.00	9.00	9.00	9.00
EH vs NV ($RH_{12,13}$)	1	1.00	1.00	1.00	1.00

BUILDING CONSTRUCTION PROJECT 3

Evaluated by five experts

Hazardous events	*Experts*	*Probability of occurrence*					*Severity of consequence*					*Probability of consequence*				
		Score	Converted STFN				Score	Converted STFN				Score	Converted STFN			
FH-01 Working platform	*E1 (0.25)*	(2,3)	2	2	3	3	(4,5)	4	4	5	5	2	2	2	2	2
	E2 (0.25)	(3,4)	3	3	4	4	(2,3)	2	2	3	3	2	2	2	2	2
	E3 (0.22)	3	3	3	3	3	(4,5)	4	4	5	5	4	4	4	4	4
	E4 (0.14)	(4,5)	4	4	5	5	(2,3,4)	2	3	3	4	(4,5)	4	4	5	5
	E5 (0.14)	(2,3,4,5)	2	3	4	5	(2,3,4,5)	2	3	4	5	(3,4,5)	3	4	4	5
FH-02 Erection of scaffolding	*E1 (0.25)*	2	2	2	2	2	(2,3)	2	2	3	3	2	2	2	2	2
	E2 (0.25)	(3,4)	3	3	4	4	3	3	3	3	3	2	2	2	2	2
	E3 (0.22)	4	4	4	4	4	(3,4)	3	3	4	4	3	3	3	3	3
	E4 (0.14)	(3,4,5)	2	4	4	5	(3,4,5)	3	3	4	5	(4,5)	4	4	5	5
	E5 (0.14)	(3,4,5)	3	4	4	5	(2,3,4,5)	2	3	4	5	(3,4,5)	3	4	4	5
FH-03 Climbing cranes	*E1 (0.25)*	3	3	3	3	3	5	5	5	5	5	2	2	2	2	2
	E2 (0.25)	(4,5)	4	4	5	5	3	3	3	3	3	3	3	3	3	3
	E3 (0.22)	(4,5)	4	4	5	5	5	5	5	5	5	3	3	3	3	3
	E4 (0.14)	(3,4,5)	3	4	4	5	(3,4)	3	3	4	4	(4,5)	4	4	5	5
	E5 (0.14)	(2,3,4,5)	2	3	4	5	(2,3,4,5)	2	3	4	5	(3,4,5)	3	4	4	5
FH-04 Temporary ladder	*E1 (0.25)*	2	2	2	2	2	3	3	3	3	3	2	2	2	2	2
	E2 (0.25)	(3,4)	3	3	4	4	3	3	3	3	3	2	2	2	2	2
	E3 (0.22)	4	4	4	4	4	(3,4)	3	3	4	4	(2,3)	2	2	3	3
	E4 (0.14)	(4,5)	4	4	5	5	(2,3,4)	2	3	3	4	(4,5)	4	4	5	5
	E5 (0.14)	(3,4)	3	3	4	4	(2,3,4)	2	3	3	4	(3,4,5)	3	4	4	5
FH-05 Hole in the ground	*E1 (0.25)*	3	3	3	3	3	(4,5)	4	4	5	5	3	3	3	3	3
	E2 (0.25)	(3,4)	3	3	4	4	(4,5)	4	4	5	5	(4,5)	4	4	5	5
	E3 (0.22)	(4,5)	4	4	5	5	5	5	5	5	5	(2,3)	2	2	3	3
	E4 (0.14)	(4,5)	4	4	5	5	(3,4,5)	3	3	4	5	5	5	5	5	5
	E5 (0.14)	(3,4,5)	3	4	4	5	(2,3,4,5)	2	3	4	5	(3,4,5)	3	4	4	5
FH-06 Working on height unprotected	*E1 (0.25)*	(4,5)	4	4	4	4	(3,4)	3	3	4	4	3	3	3	3	3
	E2 (0.25)	4	4	4	4	4	(3,5)	3	3	5	5	(4,5)	4	4	5	5
	E3 (0.22)	(4,5)	4	4	5	5	(3,4)	3	3	4	4	3	3	3	3	3
	E4 (0.14)	(4,5)	4	4	5	5	(2,3,4)	2	3	3	4	(4,5)	4	4	5	5
	E5 (0.14)	(4,5)	4	4	5	5	(2,3,4,5)	2	3	4	5	(3,4,5)	3	4	4	5
FH-07 Through opening elevator shaft	*E1 (0.25)*	4	4	4	4	4	5	5	5	5	5	2	2	2	2	2
	E2 (0.25)	3	3	3	3	3	5	5	5	5	5	(3,4)	3	3	4	4
	E3 (0.22)	4	4	4	4	4	5	5	5	5	5	(2,3)	2	2	3	3
	E4 (0.14)	(3,4,5)	3	4	4	5	(4,5)	4	4	5	5	(5,6)	5	5	6	6
	E5 (0.14)	(2,3,4,5)	2	3	4	5	(2,3,4,5)	2	3	4	5	(3,4,5,6)	3	4	5	6
FO-08 Part of climbing cranes, scaffolds	*E1 (0.25)*	3	3	3	3	3	(4,5)	4	4	5	5	(3,4)	3	3	4	4
	E2 (0.25)	3	3	3	3	3	4	4	4	4	4	(3,4)	3	3	4	4
	E3 (0.22)	3	3	3	3	3	(3,4)	3	3	4	4	(2,3)	2	2	3	3
	E4 (0.14)	(3,4,5)	3	4	4	5	(2,3,4)	2	3	3	4	4	4	4	4	4
	E5 (0.14)	(3,4)	3	3	4	4	(2,3,4,5)	2	3	4	5	(3,4,5)	3	4	4	5
FO-09 Operating, cleaning and clearing	*E1 (0.25)*	(3,4)	3	3	4	4	3	3	3	3	3	(2,3)	2	2	3	3
	E2 (0.25)	3	3	3	3	3	3	3	3	3	3	(2,3)	2	2	3	3
	E3 (0.22)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	2	2	2	2	2
	E4 (0.14)	(3,4,5)	3	4	4	5	(2,3)	2	2	3	3	4	4	4	4	4
	E5 (0.14)	(3,4,5)	3	4	4	5	(2,3,4)	2	3	3	4	(3,4,5)	3	4	4	5
FO-10 Blown by wind	*E1 (0.25)*	(3,4)	3	3	4	4	2	2	2	2	2	(3,4)	3	3	4	4
	E2 (0.25)	4	4	4	4	4	3	3	3	3	3	3	3	3	3	3
	E3 (0.22)	4	4	4	4	4	(2,3)	2	2	3	3	2	2	2	2	2
	E4 (0.14)	(2,3,4)	2	3	3	4	(1,2,3)	1	2	2	3	(3,4)	3	3	4	4
	E5 (0.14)	(2,3,4,5)	2	3	4	5	(2,3,4)	2	3	3	4	(4,5)	4	4	5	5
MH-11 Hoists	*E1 (0.25)*	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	E2 (0.25)	(3,4)	3	3	4	4	4	4	4	4	4	4	4	4	4	4
	E3 (0.22)	4	4	4	4	4	3	3	3	3	3	2	2	2	2	2
	E4 (0.14)	(3,4,5)	3	4	4	5	(2,3)	2	2	3	3	(4,5)	4	4	5	5
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3,4,5)	2	3	4	5	(4,5,6)	4	5	5	6
MH-12 Mobile crane lifting	*E1 (0.25)*	4	4	4	4	4	4	4	4	4	4	2	2	2	2	2
	E2 (0.25)	(3,4)	3	3	4	4	4	4	4	4	4	3	3	3	3	3
	E3 (0.22)	4	4	4	4	4	(4,5)	4	4	5	5	2	2	2	2	2

	E4 (0.14)	(3,4,5)	3	4	4	5	(1,2,3)	1	2	2	3	(4,5)	4	4	5	5
	E5 (0.14)	(2,3,4,5)	2	3	4	5	(2,3,4,5)	2	3	4	5	(3,4,5,6)	3	4	5	6
EQ-13 Cutting machine	*E1 (0.25)*	(3,4)	3	3	4	4	(2,3)	2	2	3	3	2	2	2	2	2
	E2 (0.25)	(3,4)	3	3	4	4	(2,3)	2	2	3	3	2	2	2	2	2
	E3 (0.22)	5	5	5	5	5	4	4	4	4	4	2	2	2	2	2
	E4 (0.14)	(4,5)	4	4	5	5	(2,3,4)	2	3	3	4	(4,5)	4	4	5	5
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3,4)	2	3	3	4	(4,5)	4	4	5	5
EQ-14 Steel bar bending machine	*E1 (0.25)*	(2,3)	2	2	3	3	2	2	2	2	2	(1,2)	1	1	2	2
	E2 (0.25)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	2	2	2	2	2
	E3 (0.22)	(2,3)	2	2	3	3	4	4	4	4	4	2	2	2	2	2
	E4 (0.14)	(4,5)	4	4	5	5	(2,3,4)	2	3	3	4	(4,5)	4	4	5	5
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3,4)	2	3	3	4	(3,4,5)	3	4	4	5
EQ-15 Grinder machine	*E1 (0.25)*	(2,3)	2	2	3	3	2	2	2	2	2	2	2	2	2	2
	E2 (0.25)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	(2,3)	2	2	3	3
	E3 (0.22)	(3,4)	3	3	4	4	5	5	5	5	5	(2,3)	2	2	3	3
	E4 (0.14)	(3,4,5)	3	4	4	5	(1,2,3)	1	2	2	3	(4,5)	4	4	5	5
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3,4,5)	2	3	4	5	(4,5,6)	4	5	5	6
EQ-16 Welding machine	*E1 (0.25)*	(2,3)	2	2	3	3	2	2	2	2	2	(2,3)	2	2	3	3
	E2 (0.25)	(2,3)	2	2	3	3	3	3	3	3	3	(2,3)	2	2	3	3
	E3 (0.22)	(2,3)	2	2	3	3	4	4	4	4	4	2	2	2	2	2
	E4 (0.14)	(4,5)	4	4	5	5	(1,2,3)	1	2	2	3	(4,5)	4	4	5	5
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3,4)	2	3	3	4	(3,4,5)	3	4	4	5
EL-17 Wires	*E1 (0.25)*	3	3	3	3	3	3	3	3	3	3	2	2	2	2	2
	E2 (0.25)	(2,3)	2	2	3	3	(3,5)	3	3	5	5	2	2	2	2	2
	E3 (0.22)	(3,4)	3	3	4	4	5	5	5	5	5	3	3	3	3	3
	E4 (0.14)	(3,4,5)	3	4	4	5	(1,2,3)	1	2	2	3	(4,5)	4	4	5	5
	E5 (0.14)	(2,3,4,5)	2	3	4	5	(2,3,4,5)	2	3	4	5	(4,5,6)	4	5	5	6
EL-18 Electrical work	*E1 (0.25)*	3	3	3	3	3	3	3	3	3	3	2	2	2	2	2
	E2 (0.25)	(3,4)	3	3	4	4	(3,4)	3	3	4	4	3	3	3	3	3
	E3 (0.22)	(3,4)	3	3	4	4	(3,4)	3	3	4	4	2	2	2	2	2
	E4 (0.14)	(2,3,4)	2	3	3	4	(3,4,5)	3	4	4	5	(4,5)	4	4	5	5
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3,4,5)	2	3	4	5	(3,4,5)	3	4	4	5
EL-19 Overhead power lines	*E1 (0.25)*	2	2	2	2	2	3	3	3	3	3	2	2	2	2	2
	E2 (0.25)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	(2,3)	2	2	3	3
	E3 (0.22)	4	4	4	4	4	4	4	4	4	4	(2,3)	2	2	3	3
	E4 (0.14)	(2,3,4)	2	3	3	4	(2,3,4)	2	3	3	4	(3,4)	3	3	4	4
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3,4)	2	3	3	4	(3,4,5)	3	4	4	5
EL-20 Arcing welding machine	*E1 (0.25)*	(2,3)	2	2	3	3	3	3	3	3	3	2	2	2	2	2
	E2 (0.25)	(2,3)	2	2	3	3	3	3	3	3	3	(2,3)	2	2	3	3
	E3 (0.22)	3	3	3	3	3	4	4	4	4	4	(2,3)	2	2	3	3
	E4 (0.14)	(3,4,5)	3	4	4	5	(2,3,4)	2	3	3	4	(2,3,4)	2	3	3	4
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3,4)	2	3	3	4	(3,4,5)	3	4	4	5
ST-21 Tripping over building materials	*E1 (0.25)*	(2,3)	2	2	3	3	2	2	2	2	2	3	3	3	3	3
	E2 (0.25)	(2,3)	2	2	3	3	2	2	2	2	2	(2,3)	2	2	3	3
	E3 (0.22)	3	3	3	3	3	(3,4)	3	3	4	4	3	3	3	3	3
	E4 (0.14)	(3,4,5)	3	4	4	5	(2,3)	2	2	3	3	(3,4)	3	3	4	4
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3,4,5)	2	3	4	5	(3,4,5)	3	4	4	5
ST-22 Slipping wet surfaces	*E1 (0.25)*	(3,4)	3	3	4	4	2	2	2	2	2	2	2	2	2	2
	E2 (0.25)	(2,3)	2	2	3	3	2	2	2	2	2	3	3	3	3	3
	E3 (0.22)	3	3	3	3	3	(3,4)	3	3	4	4	3	3	3	3	3
	E4 (0.14)	(4,5)	4	4	5	5	(1,2,3)	1	2	2	3	(2,3,4)	2	3	3	4
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3,4)	2	3	3	4	(3,4,5)	3	4	4	5
ST-23 Trips caused by small change in level	*E1 (0.25)*	(3,4)	3	3	4	4	2	2	2	2	2	2	2	2	2	2
	E2 (0.25)	(1,2)	1	1	2	2	(1,2)	1	1	2	2	(2,3)	2	2	3	3
	E3 (0.22)	3	3	3	3	3	(2,3)	2	2	3	3	3	3	3	3	3
	E4 (0.14)	(2,3,4)	2	3	3	4	(1,2)	1	1	2	2	(3,4,5)	3	4	4	5
	E5 (0.14)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	(3,4)	3	3	4	4
ST-24 Trips caused by water pipes, rebar	*E1 (0.25)*	(3,4)	3	3	4	4	(2,3)	2	2	3	3	3	3	3	3	3
	E2 (0.25)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	(2,3)	2	2	3	3
	E3 (0.22)	(2,3)	2	2	3	3	3	3	3	3	3	(2,3)	2	2	3	3
	E4 (0.14)	(2,3,4)	2	3	3	4	(2,3,4)	2	3	3	4	(3,4,5)	3	4	4	5
	E5 (0.14)	(2,3)	2	2	3	3	(2,3,4)	2	3	3	4	(3,4,5)	3	4	4	5
TH-25 Collison with another vehicles	*E1 (0.25)*	(1,2)	1	1	2	2	3	3	3	3	3	1	1	1	1	1
	E2 (0.25)	3	3	3	3	3	(2,3)	2	2	3	3	2	2	2	2	2

	E3 (0.22)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	2	2	2	2	2
	E4 (0.14)	(2,3,4)	2	3	3	4	(3,4,5)	3	4	4	5	(2,3)	2	2	3	3
	E5 (0.14)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	(3,4)	3	3	4	4
TH-26 Collision with plant/people	*E1 (0.25)*	(1,2)	1	1	2	2	4	4	4	4	4	(1,2)	1	1	2	2
	E2 (0.25)	3	3	3	3	3	(2,3)	2	2	3	3	2	2	2	2	2
	E3 (0.22)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	2	2	2	2	2
	E4 (0.14)	(2,3,4)	2	3	3	4	(2,3,4)	2	3	3	4	(3,4,5)	3	4	4	5
	E5 (0.14)	(2,3)	2	2	3	3	(2,3,4)	2	3	3	4	(3,4)	3	3	4	4
FE-27 Hot work	*E1 (0.25)*	(2,3)	2	2	3	3	2	2	2	2	2	2	2	2	2	2
	E2 (0.25)	(2,3)	2	2	3	3	3	3	3	3	3	(2,3)	2	2	3	3
	E3 (0.22)	(4,5)	4	4	5	5	(4,5)	4	4	5	5	3	3	3	3	3
	E4 (0.14)	(4,5)	4	4	5	5	(2,3)	2	2	3	3	(4,5)	4	4	5	5
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3)	2	2	3	3	(3,4,5)	3	4	4	5
FE-28 Working near flammables	*E1 (0.25)*	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
	E2 (0.25)	3	3	3	3	3	2	2	2	2	2	(2,3)	2	2	3	3
	E3 (0.22)	(2,3)	2	2	3	3	(4,5)	4	4	5	5	2	2	2	2	2
	E4 (0.14)	(4,5)	4	4	5	5	(3,4,5)	3	3	4	5	(4,5,6)	4	5	5	6
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3,4,5)	2	3	4	5	(3,4,5)	3	4	4	5
FE-29 Gas cylinder or hose leakage	*E1 (0.25)*	1	1	1	1	1	(2,3)	2	2	3	3	2	2	2	2	2
	E2 (0.25)	2	2	2	2	2	3	3	3	3	3	(2,3)	2	2	3	3
	E3 (0.22)	(2,3)	2	2	3	3	(4,5)	4	4	5	5	2	2	2	2	2
	E4 (0.14)	(4,5)	4	4	5	5	(4,5)	4	4	5	5	(3,4,5)	3	4	4	5
	E5 (0.14)	(2,3,4,5)	2	3	4	5	(2,3,4)	2	3	3	4	(3,4,5)	3	4	4	5
FE-30 Fire extinguisher has been discharged	*E1 (0.25)*	2	2	2	2	2	(3,4)	3	3	4	4	(1,2)	1	1	2	2
	E2 (0.25)	2	2	2	2	2	3	3	3	3	3	2	2	2	2	2
	E3 (0.22)	(3,4)	3	3	4	4	(4,5)	4	4	5	5	2	2	2	2	2
	E4 (0.14)	(4,5)	4	4	5	5	(2,3,4)	2	3	3	4	(4,5,6)	4	5	5	6
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3,4,5)	2	3	4	5	(3,4,5)	3	4	4	5
ES-31 Cement dust	*E1 (0.25)*	4	4	4	4	4	(2,3)	2	2	3	3	4	4	4	4	4
	E2 (0.25)	(2,3)	2	2	3	3	2	2	2	2	2	(2,3)	2	2	3	3
	E3 (0.22)	3	3	3	3	3	(3,4)	3	3	4	4	3	3	3	3	3
	E4 (0.14)	(4,5)	4	4	5	5	(2,3,4)	2	3	3	4	(3,4,5)	3	4	4	5
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3)	2	2	3	3	(3,4,5)	3	4	4	5
CO-32 Collapse of boom(Cranes)	*E1 (0.25)*	1	1	1	1	1	(4,5)	4	4	5	5	1	1	1	1	1
	E2 (0.25)	(2,3)	2	2	3	3	4	4	4	4	4	(3,5)	3	3	5	5
	E3 (0.22)	(2,3)	2	2	3	3	5	5	5	5	5	1	1	1	1	1
	E4 (0.14)	(3,4)	3	3	4	4	(3,4,5)	3	3	4	5	(5,6)	5	5	6	6
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3,4,5)	2	3	4	5	(3,4)	3	3	4	4
CO-33 Collapse of scaffolding	*E1 (0.25)*	2	2	2	2	2	(4,5)	4	4	5	5	(1,2)	1	1	2	2
	E2 (0.25)	(2,3)	2	2	3	3	4	4	4	4	4	(3,5)	3	3	5	5
	E3 (0.22)	3	3	3	3	3	(4,5)	4	4	5	5	(1,2)	1	1	2	2
	E4 (0.14)	(3,4)	3	3	4	4	(4,5)	4	4	5	5	(5,6)	5	5	6	6
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3,4,5)	2	3	4	5	(3,4)	3	3	4	4
CO-34 Steel sheet piles	*E1 (0.25)*	(2,3)	2	2	3	3	(2,3)	2	2	3	3	2	2	2	2	2
	E2 (0.25)	(3,4)	3	3	4	4	(3,4)	3	3	4	4	(2,4)	2	2	4	4
	E3 (0.22)	(2,3)	2	2	3	3	(3,4)	3	3	4	4	(1,2)	1	1	2	2
	E4 (0.14)	(2,3,4)	2	3	3	4	(2,3,4)	2	3	3	4	4	4	4	4	4
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3,4,5)	2	3	4	5	(3,4)	3	3	4	4
CO-35 Kingpost	*E1 (0.25)*	1	1	1	1	1	(4,5)	4	4	5	5	1	1	1	1	1
	E2 (0.25)	(1,3)	1	1	3	3	(3,4)	3	3	4	4	(2,4)	2	2	4	4
	E3 (0.22)	3	3	3	3	3	(3,4)	3	3	4	4	1	1	1	1	1
	E4 (0.14)	(2,3,4)	2	3	3	4	(2,3,4)	2	3	3	4	(4,5)	4	4	5	5
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3,4,5)	2	3	4	5	(3,4)	3	3	4	4
CS-36 Deep excavations	*E1 (0.25)*	2	2	2	2	2	4	4	4	4	4	2	2	2	2	2
	E2 (0.25)	(1,3)	1	1	3	3	(2,3)	2	2	3	3	(2,4)	2	2	4	4
	E3 (0.22)	3	3	3	3	3	4	4	4	4	4	(1,2)	1	1	2	2
	E4 (0.14)	(4,5)	4	4	5	5	(3,4,5)	3	3	4	5	(4,5)	4	4	5	5
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3,4,5)	2	3	4	5	(3,4)	3	3	4	4
CS-37 Closed tanks	*E1 (0.25)*	2	2	2	2	2	(3,4)	3	3	4	4	(2,3)	2	2	3	3
	E2 (0.25)	(1,3)	1	1	3	3	(2,3)	2	2	3	3	(2,4)	2	2	4	4
	E3 (0.22)	(2,3)	2	2	3	3	(4,5)	4	4	5	5	(1,2)	1	1	2	2
	E4 (0.14)	(4,5)	4	4	5	5	(3,4,5)	3	3	4	5	(3,4)	3	3	4	4
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3,4,5)	2	3	4	5	(3,4)	3	3	4	4
EH-38 Poor work posture	*E1 (0.25)*	3	3	3	3	3	3	3	3	3	3	2	2	2	2	2
	E2 (0.25)	(1,2)	1	1	2	2	(2,3)	2	2	3	3	2	2	2	2	2
	E3 (0.22)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	2	2	2	2	2
	E4 (0.14)	(3,4,5)	3	4	4	5	(2,3)	2	2	3	3	(4,5,6)	4	5	5	6

	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3)	2	2	3	3	(3,4,5)	3	4	4	5
EH-39 Extreme muscular exertion	*E1 (0.25)*	2	2	2	2	2	3	3	3	3	3	(2,3,4)	2	3	3	4
	E2 (0.25)	(2,3)	2	2	3	3	(2,4,5)	2	4	4	5	(5,6)	5	5	6	6
	E3 (0.22)	(2,3)	2	2	3	3	3	3	3	3	3	2	2	2	2	2
	E4 (0.14)	(4,5)	4	4	5	5	(3,4)	3	3	4	4	(4,5,6)	4	5	5	6
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3,4)	2	3	3	4	(3,4,5)	3	4	4	5
NV-40 Piling	*E1 (0.25)*	(4,5)	4	4	5	5	(2,3)	2	2	3	3	(3,4)	3	3	4	4
	E2 (0.25)	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4
	E3 (0.22)	2	2	2	2	2	3	3	3	3	3	(2,3)	2	2	3	3
	E4 (0.14)	(4,5)	4	4	5	5	(3,4)	3	3	4	4	(4,5)	4	4	5	5
	E5 (0.14)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	(3,4,5)	3	4	4	5
NV-41 Excavation	*E1 (0.25)*	4	4	4	4	4	(3,4)	3	3	4	4	(2,3)	2	2	3	3
	E2 (0.25)	3	3	3	3	3	(3,4)	3	3	4	4	3	3	3	3	3
	E3 (0.22)	(2,3)	2	2	3	3	(3,4)	3	3	4	4	(2,3)	2	2	3	3
	E4 (0.14)	(4,5)	4	4	5	5	(2,3)	2	2	3	3	(4,5,6)	4	5	5	6
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3,4)	2	3	3	4	(3,4,5)	3	4	4	5
NV-42 Hammering	*E1 (0.25)*	5	5	5	5	5	(2,3)	2	2	3	3	(2,3)	2	2	3	3
	E2 (0.25)	3	3	3	3	3	(3,5)	3	3	5	5	4	4	4	4	4
	E3 (0.22)	2	2	2	2	2	(3,4)	3	3	4	4	2	2	2	2	2
	E4 (0.14)	(4,5)	4	4	5	5	(2,3)	2	2	3	3	(3,4,5)	3	4	4	5
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3)	2	2	3	3	(3,4,5)	3	4	4	5
NV-43 Vibrator machine	*E1 (0.25)*	4	4	4	4	4	(2,3)	2	2	3	3	(2,3)	2	2	3	3
	E2 (0.25)	3	3	3	3	3	3	3	3	3	3	5	5	5	5	5
	E3 (0.22)	1	1	1	1	1	2	2	2	2	2	1	1	1	1	1
	E4 (0.14)	(2,3,4)	2	3	3	4	(1,2,3)	1	2	2	3	(2,3,4)	2	3	3	4
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3)	2	2	3	3	(3,4,5)	3	4	4	5
NV-44 Hand-held power tools	*E1 (0.25)*	4	4	4	4	4	3	3	3	3	3	(2,3)	2	2	3	3
	E2 (0.25)	3	3	3	3	3	(3,4)	3	3	4	4	(4,5)	4	4	5	5
	E3 (0.22)	(2,3)	2	2	3	3	3	3	3	3	3	3	3	3	3	3
	E4 (0.14)	(4,5)	4	4	5	5	(1,2,3)	1	2	2	3	(3,4,5)	3	4	4	5
	E5 (0.14)	(2,3,4,5)	2	3	4	5	(2,3)	2	2	3	3	(3,4,5)	3	4	4	5
NV-45 Concrete pump machine	*E1 (0.25)*	2	2	2	2	2	(1,2)	1	1	2	2	(1,2,3)	1	2	2	3
	E2 (0.25)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	5	5	5	5	5
	E3 (0.22)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	2	2	2	2	2
	E4 (0.14)	(4,5)	4	4	5	5	(1,2)	1	1	2	2	(5,6)	5	5	6	6
	E5 (0.14)	(2,3,4)	2	3	3	4	(2,3)	2	2	3	3	(3,4)	3	3	4	4

Comparison by expert judgements of hazard groups in building construction project 3

Comparison	$E_1 (0.25)$					$E_2 (0.25)$					$E_3 (0.22)$					$E_4 (0.14)$				
	Score	Converted STFN				Score	Converted STFN				Score	Converted STFN				Score	Converted STFN			
FH vs FO (RH_{12})	(0.20, 0.25)	0.20	0.20	0.25	0.25	7	7.00	7.00	7.00	7.00	0.2	0.20	0.20	0.20	0.20	7	7.00	7.00	7.00	7.00
FO vs MH (RH_{23})	(5,6)	5.00	5.00	6.00	6.00	7	7.00	7.00	7.00	7.00	4	4.00	4.00	4.00	4.00	8	8.00	8.00	8.00	8.00
MH vs EQ (RH_{34})	(0.14, 0.17)	0.14	0.14	0.17	0.17	1	1.00	1.00	1.00	1.00	0.2	0.20	0.20	0.20	0.20	1	1.00	1.00	1.00	1.00
EQ vs EL (RH_{45})	1	1.00	1.00	1.00	1.00	7	7.00	7.00	7.00	7.00	0.17	0.17	0.17	0.17	0.17	1	1.00	1.00	1.00	1.00
EL vs ST (RH_{56})	(0.25, 0.33)	0.25	0.25	0.33	0.33	1	1.00	1.00	1.00	1.00	5	5.00	5.00	5.00	5.00	9	9.00	9.00	9.00	9.00
ST vs TH (RH_{67})	5	5.00	5.00	5.00	5.00	7	7.00	7.00	7.00	7.00	5	5.00	5.00	5.00	5.00	1	1.00	1.00	1.00	1.00
TH vs FE (RH_{78})	(1,2)	1.00	1.00	2.00	2.00	0.2	0.20	0.20	0.20	0.20	1	1.00	1.00	1.00	1.00	0.14	0.14	0.14	0.14	0.14
FE vs ES ($RH_{8,9}$)	(0.20, 0.25)	0.20	0.20	0.25	0.25	5	5.00	5.00	5.00	5.00	1	1.00	1.00	1.00	1.00	1	1.00	1.00	1.00	1.00
ES vs CO ($RH_{9,10}$)	(5,6)	5.00	5.00	6.00	6.00	0.2	0.20	0.20	0.20	0.20	0.13	0.13	0.13	0.13	0.13	1	1.00	1.00	1.00	1.00
CO vs CS ($RH_{10,11}$)	0.5	0.50	0.50	0.50	0.50	5	5.00	5.00	5.00	5.00	8	8.00	8.00	8.00	8.00	1	1.00	1.00	1.00	1.00
CS vs EH ($RH_{11,12}$)	(0.25, 0.33)	0.25	0.25	0.33	0.33	5	5.00	5.00	5.00	5.00	7	7.00	7.00	7.00	7.00	9	9.00	9.00	9.00	9.00
EH vs NV ($RH_{12,13}$)	(4,5)	4.00	4.00	5.00	5.00	0.2	0.20	0.20	0.20	0.20	1	1.00	1.00	1.00	1.00	1	1.00	1.00	1.00	1.00

Comparison	$E_5 (0.14)$				
	Score	Converted STFN			
FH vs FO (RH_{12})	1	1.00	1.00	1.00	1.00
FO vs MH (RH_{23})	7	7.00	7.00	7.00	7.00
MH vs EQ (RH_{34})	1	1.00	1.00	1.00	1.00
EQ vs EL (RH_{45})	1	1.00	1.00	1.00	1.00
EL vs ST (RH_{56})	5	5.00	5.00	5.00	5.00
ST vs TH (RH_{67})	1	1.00	1.00	1.00	1.00
TH vs FE (RH_{78})	0.2	0.20	0.20	0.20	0.20
FE vs ES ($RH_{8,9}$)	1	1.00	1.00	1.00	1.00
ES vs CO ($RH_{9,10}$)	5	5.00	5.00	5.00	5.00
CO vs CS ($RH_{10,11}$)	1	1.00	1.00	1.00	1.00
CS vs EH ($RH_{11,12}$)	1	1.00	1.00	1.00	1.00
EH vs NV ($RH_{12,13}$)	1	1.00	1.00	1.00	1.00

MRT RAILWAY CONSTRUCTION PROJECT 4

Evaluated by five experts

Hazardous events	*Experts*	*Probability of occurrence*					*Severity of consequence*					*Probability of consequence*				
		Score	Converted STFN				Score	Converted STFN				Score	Converted STFN			
FH-01 Working platform	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	4	4	4	4	4
	E2 (0.25)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
	E3 (0.22)	1	1	1	1	1	(4,5)	4	4	5	5	3	3	3	3	3
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3
FH-02 Erection of scaffolding	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	4	4	4	4	4
	E2 (0.25)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
	E3 (0.22)	(1,2)	1	1	2	2	(3,4)	3	3	4	4	4	4	4	4	4
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3
FH-03 Cranes	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E2 (0.25)	(1,2)	1	1	2	2	2	2	2	2	2	3	3	3	3	3
	E3 (0.22)	1	1	1	1	1	(2,3)	2	2	3	3	4	4	4	4	4
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
FH-04 Temporary ladder	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E2 (0.25)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
	E3 (0.22)	1	1	1	1	1	(2,3)	2	2	3	3	4	4	4	4	4
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3
FH-05 Hole in the ground	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E2 (0.25)	1	1	1	1	1	3	3	3	3	3	2	2	2	2	2
	E3 (0.22)	1	1	1	1	1	(3,4,5)	3	4	4	5	4	4	4	4	4
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
FH-06 Working on height unprotected	*E1 (0.25)*	4	4	4	4	4	1	1	1	1	1	3	3	3	3	3
	E2 (0.25)	(1,2)	1	1	2	2	(3,4,5)	3	4	4	5	4	4	4	4	4
	E3 (0.22)	(2,3)	2	2	3	3	(3,4,5)	3	4	4	5	5	5	5	5	5
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
FH-07 Roof work	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	4	4	4	4	4
	E2 (0.25)	1	1	1	1	1	(3,4,5)	3	4	4	5	4	4	4	4	4
	E3 (0.22)	2	2	2	2	2	(4,5)	4	4	5	5	4	4	4	4	4
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
FO-08 Part of climbing cranes, scaffolds	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E2 (0.25)	1	1	1	1	1	1	1	1	1	1	5	5	5	5	5
	E3 (0.22)	1	1	1	1	1	(4,5)	4	4	5	5	4	4	4	4	4
	E4 (0.14)	3	3	3	3	3	1	1	1	1	1	1	1	1	1	1
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3
FO-09 Operating, cleaning and clearing	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E2 (0.25)	(2,3)	2	2	3	3	1	1	1	1	1	5	5	5	5	5
	E3 (0.22)	(4,5)	4	4	5	5	(4,5)	4	4	5	5	5	5	5	5	5
	E4 (0.14)	4	4	4	4	4	1	1	1	1	1	3	3	3	3	3
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3
FO-10 Blown by wind	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E2 (0.25)	1	1	1	1	1	1	1	1	1	1	4	4	4	4	4
	E3 (0.22)	1	1	1	1	1	(4,5)	4	4	5	5	3	3	3	3	3
	E4 (0.14)	4	4	4	4	4	1	1	1	1	1	4	4	4	4	4
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3
MH-11 Hoists	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E2 (0.25)	1	1	1	1	1	2	2	2	2	2	4	4	4	4	4
	E3 (0.22)	1	1	1	1	1	4	4	4	4	4	3	3	3	3	3
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3
MH-12 Manual lifting	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	4	4	4	4	4
	E2 (0.25)	1	1	1	1	1	2	2	2	2	2	4	4	4	4	4
	E3 (0.22)	1	1	1	1	1	(1,2,3)	1	2	2	3	3	3	3	3	3
	E4 (0.14)	3	3	3	3	3	2	2	2	2	2	3	3	3	3	3
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3

EQ-13 Cutting machine	*E1 (0.25)*	1	1	1	1	1	2	2	2	2	2	4	4	4	4	4
	E2 (0.25)	1	1	1	1	1	(1,2)	1	1	2	2	4	4	4	4	4
	E3 (0.22)	1	1	1	1	1	(4,5)	4	4	5	5	(3,4)	3	3	4	4
	E4 (0.14)	4	4	4	4	4	2	2	2	2	2	4	4	4	4	4
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	4	4	4	4	4
EQ-14 Steel bar bending machine	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E2 (0.25)	1	1	1	1	1	(1,2)	1	1	2	2	4	4	4	4	4
	E3 (0.22)	1	1	1	1	1	(4,5)	4	4	5	5	(3,4)	3	3	4	4
	E4 (0.14)	4	4	4	4	4	1	1	1	1	1	4	4	4	4	4
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
EQ-15 Grinder machine	*E1 (0.25)*	1	1	1	1	1	2	2	2	2	2	4	4	4	4	4
	E2 (0.25)	1	1	1	1	1	(1,2)	1	1	2	2	4	4	4	4	4
	E3 (0.22)	(1,2)	1	1	2	2	(4,5)	4	4	5	5	5	5	5	5	5
	E4 (0.14)	4	4	4	4	4	2	2	2	2	2	4	4	4	4	4
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3
EQ-16 Welding machine	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	4	4	4	4	4
	E2 (0.25)	1	1	1	1	1	(1,2)	1	1	2	2	3	3	3	3	3
	E3 (0.22)	(1,2)	1	1	2	2	(2,3)	2	2	3	3	5	5	5	5	5
	E4 (0.14)	3	3	3	3	3	1	1	1	1	1	3	3	3	3	3
	E5 (0.14)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
EL-17 Wires	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E2 (0.25)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E3 (0.22)	1	1	1	1	1	(1,2)	1	1	2	2	4	4	4	4	4
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
EL-18 Electrical work	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E2 (0.25)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E3 (0.22)	1	1	1	1	1	(1,2)	1	1	2	2	4	4	4	4	4
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
EL-19 Overhead power lines	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E2 (0.25)	(1,2)	1	1	2	2	1	1	1	1	1	(1,2)	1	1	2	2
	E3 (0.22)	(2,3)	2	2	3	3	(4,5)	4	4	5	5	5	5	5	5	5
	E4 (0.14)	1	1	1	1	1	4	4	4	4	4	3	3	3	3	3
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3
EL-20 Arcing welding machine	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E2 (0.25)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E3 (0.22)	1	1	1	1	1	(1,2)	1	1	2	2	5	5	5	5	5
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	3	3	3	3	3
ST-21 Tripping over building materials	*E1 (0.25)*	4	4	4	4	4	1	1	1	1	1	2	2	2	2	2
	E2 (0.25)	(2,3)	2	2	3	3	(3,4)	3	3	4	4	5	5	5	5	5
	E3 (0.22)	(1,2,3)	1	2	2	3	(1,2)	1	1	2	2	5	5	5	5	5
	E4 (0.14)	2	2	2	2	2	2	2	2	2	2	4	4	4	4	4
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
ST-22 Slipping wet surfaces	*E1 (0.25)*	4	4	4	4	4	1	1	1	1	1	2	2	2	2	2
	E2 (0.25)	2	2	2	2	2	3	3	3	3	3	5	5	5	5	5
	E3 (0.22)	(2,3)	2	2	3	3	(1,2)	1	1	2	2	5	5	5	5	5
	E4 (0.14)	3	3	3	3	3	2	2	2	2	2	4	4	4	4	4
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
ST-23 Trips caused by small change in level	*E1 (0.25)*	4	4	4	4	4	1	1	1	1	1	4	4	4	4	4
	E2 (0.25)	2	2	2	2	2	3	3	3	3	3	5	5	5	5	5
	E3 (0.22)	(2,3)	2	2	3	3	(1,2)	1	1	2	2	(5,6)	5	5	6	6
	E4 (0.14)	3	3	3	3	3	2	2	2	2	2	4	4	4	4	4
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
ST-24 Trips caused by water pipes, rebar	*E1 (0.25)*	1	1	1	1	1	2	2	2	2	2	4	4	4	4	4
	E2 (0.25)	1	1	1	1	1	3	3	3	3	3	4	4	4	4	4
	E3 (0.22)	(1,2)	1	1	2	2	(1,2,3)	1	2	2	3	5	5	5	5	5
	E4 (0.14)	2	2	2	2	2	2	2	2	2	2	4	4	4	4	4
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
FE-25 Hot work	*E1 (0.25)*	1	1	1	1	1	2	2	2	2	2	4	4	4	4	4
	E2 (0.25)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E3 (0.22)	1	1	1	1	1	(4,5)	4	4	5	5	4	4	4	4	4
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2

FE-26 Working near flammables	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E2 (0.25)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E3 (0.22)	1	1	1	1	1	(4,5)	4	4	5	5	4	4	4	4	4
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
FE-27 Gas cylinder or hose leakage	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E2 (0.25)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E3 (0.22)	1	1	1	1	1	(3,4,5)	3	4	4	5	4	4	4	4	4
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
FE-28 Fire extinguisher has been discharged	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E2 (0.25)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E3 (0.22)	1	1	1	1	1	4	4	4	4	4	4	4	4	4	4
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2
EH-29 Poor work posture	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E2 (0.25)	2	2	2	2	2	(2,3)	2	2	3	3	4	4	4	4	4
	E3 (0.22)	(1,2)	1	1	2	2	(2,3)	2	2	3	3	(5,6)	5	5	6	6
	E4 (0.14)	2	2	2	2	2	2	2	2	2	2	4	4	4	4	4
	E5 (0.14)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
EH-30 Extreme muscular exertion	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	4	4	4	4	4
	E2 (0.25)	(2,3)	2	2	3	3	(2,3)	2	2	3	3	4	4	4	4	4
	E3 (0.22)	(1,2)	1	1	2	2	(2,3)	2	2	3	3	(5,6)	5	5	6	6
	E4 (0.14)	2	2	2	2	2	2	2	2	2	2	4	4	4	4	4
	E5 (0.14)	1	1	1	1	1	2	2	2	2	2	3	3	3	3	3
NV-31 Piling	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	4	4	4	4	4
	E2 (0.25)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E3 (0.22)	1	1	1	1	1	(4,5)	4	4	5	5	(3,4)	3	3	4	4
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
NV-32 Excavation	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	4	4	4	4	4
	E2 (0.25)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E3 (0.22)	1	1	1	1	1	(4,5)	4	4	5	5	(3,4)	3	3	4	4
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
NV-33 Hammering	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	4	4	4	4	4
	E2 (0.25)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E3 (0.22)	1	1	1	1	1	(4,5)	4	4	5	5	3	3	3	3	3
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
NV-34 Vibrator machine	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	4	4	4	4	4
	E2 (0.25)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E3 (0.22)	1	1	1	1	1	(4,5)	4	4	5	5	(2,3)	2	2	3	3
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
NV-35 Hand-held power tools	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E2 (0.25)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E3 (0.22)	1	1	1	1	1	(4,5)	4	4	5	5	(3,4)	3	3	4	4
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
NV-36 Concrete pump machine	*E1 (0.25)*	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E2 (0.25)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E3 (0.22)	1	1	1	1	1	(3,4)	3	3	4	4	3	3	3	3	3
	E4 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	E5 (0.14)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Comparison by expert judgements of hazard groups in MRT railway construction project 4

Comparison	E_1 (0.25)					E_2 (0.25)					E_3 (0.22)					E_4 (0.14)				
	Score	Converted STFN				Score	Converted STFN				Score	Converted STFN				Score	Converted STFN			
FH vs FO (RH_{12})	9.00	9.00	9.00	9.00	9.00	1.00	1.00	1.00	1.00	1.00	2.00	2.00	2.00	2.00	2.00	1.00	1.00	1.00	1.00	1.00
FO vs MH (RH_{23})	7.00	7.00	7.00	7.00	7.00	5.00	5.00	5.00	5.00	5.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00	7.00
MH vs EQ (RH_{34})	1.00	1.00	1.00	1.00	1.00	2.00	2.00	2.00	2.00	2.00	0.20	0.20	0.20	0.20	0.20	1.00	1.00	1.00	1.00	1.00
EQ vs EL (RH_{45})	0.20	0.20	0.20	0.20	0.20	0.17	0.17	0.17	0.17	0.17	3.00	3.00	3.00	3.00	3.00	1.00	1.00	1.00	1.00	1.00
EL vs ST (RH_{56})	5.00	5.00	5.00	5.00	5.00	7.00	7.00	7.00	7.00	7.00	6.00	6.00	6.00	6.00	6.00	7.00	7.00	7.00	7.00	7.00
ST vs FE (RH_{67})	0.11	0.11	0.11	0.11	0.11	0.14	0.14	0.14	0.14	0.14	0.17	0.17	0.17	0.17	0.17	0.14	0.14	0.14	0.14	0.14
FE vs EH ($RH_{7,8}$)	9.00	9.00	9.00	9.00	9.00	4.00	4.00	4.00	4.00	4.00	5.00	5.00	5.00	5.00	5.00	7.00	7.00	7.00	7.00	7.00
EH vs NV ($RH_{8,9}$)	0.20	0.20	0.20	0.20	0.20	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Comparison	E_5 (0.14)				
	Score	Converted STFN			
FH vs FO (RH_{12})	1.00	1.00	1.00	1.00	1.00
FO vs MH (RH_{23})	4.00	4.00	4.00	4.00	4.00
MH vs EQ (RH_{34})	0.25	0.25	0.25	0.25	0.25
EQ vs EL (RH_{45})	3.00	3.00	3.00	3.00	3.00
EL vs ST (RH_{56})	0.33	0.33	0.33	0.33	0.33
ST vs FE (RH_{67})	3.00	3.00	3.00	3.00	3.00
FE vs EH ($RH_{7,8}$)	1.00	1.00	1.00	1.00	1.00
EH vs NV ($RH_{8,9}$)	1.00	1.00	1.00	1.00	1.00

APPENDIX F.

JOURNAL PAPER

Sansakorn, P. and An, M. (2015) "*Development of Risk Assessment and Occupational Safety Management Model for Building Construction Projects", International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering, Vol. 9, No. 9, pp.*