CONSTRUCTION SUPPLY CHAIN RISK MANAGEMENT: A CASE STUDY

By

Mr. Jia MAO

A Thesis Submitted in Partial Fulfillment of the Requirements
for Master of Engineering ENGINEERING MANAGEMENT
Department of INDUSTRIAL ENGINEERING AND MANAGEMENT
Silpakorn University
Academic Year 2024

-

โดย

Mr.Jia Mao

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรวิศวกรรมศาสตรมหาบัณฑิต
สาขาวิชาการจัดการงานวิศวกรรม แผน ก แบบ ก 2
ภาควิชาวิศวกรรมอุตสาหการและการจัดการ
มหาวิทยาลัยศิลปากร
ปีการศึกษา 2567

CONSTRUCTION SUPPLY CHAIN RISK MANAGEMENT:
A CASE STUDY

By

Mr. Jia MAO

A Thesis Submitted in Partial Fulfillment of the Requirements
for Master of Engineering ENGINEERING MANAGEMENT
Department of INDUSTRIAL ENGINEERING AND MANAGEMENT
Academic Year 2024

Title	CONSTRUCTION SUPPLY CHAIN RISK MANAGEMENT: A CASE STUDY
By	Mr. Jia MAO
Field of Study	ENGINEERING MANAGEMENT
Advisor	Associate Professor Choosak Pornsing, Ph.D.

Faculty of Engineering and Industrial Technology, Silpakorn University in Partial Fulfillment of the Requirements for the Master of Engineering

Dean of Faculty of Engineering and Industrial Technology
(Assistant Professor Arunsri Leejeerajumnean, Ph.D.)

Approved by

Chair person
(Assistant Professor Noppakun Sangkhiew, Ph.D.)

Advisor
(Associate Professor Choosak Pornsing, Ph.D.)

External Examiner
(Assistant Professor Pattrawet Tharawetcharak, Ph.D.)

650920036 : Major ENGINEERING MANAGEMENT
Keyword : Supply chain risk, multiple-attribute decision-making, grey relational analysis, construction industry

Mr. Jia MAO : CONSTRUCTION SUPPLY CHAIN RISK MANAGEMENT: A CASE STUDY Thesis advisor : Associate Professor Choosak Pornsing, Ph.D.

Managing supply chains involves not only the delivery of commodities but also the consideration of the disruption caused by various forms of uncertainty. Consequently, in order to follow a risk reduction strategy, supply chain management needs to start with risk analysis and appraisal. The grey relational analysis is a decision-making method that considers many attributes and is utilized in this article. In construction supply chain management, fifteen experts from a sample construction business in Kunming were consulted to validate three essential risk factors and fourteen sub-risk factors that were obtained from the literature. Following that, a group of five decision-makers from a sample construction project participated in the evaluation of five different suppliers of steel material. Based on the significant risk variables of time, cost, and quality, the outcome demonstrated that a regional supplier, B2, delivers superior performance compared to other rivals. The GRA procedure demonstrated that it is a straightforward method that can be implemented in actual reality. Another recommendation made by the study was to consider two specified factors with caution.

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to Associate Professor Dr. Choosak Pornsing, who served as my thesis advisor. I am genuinely thankful for his invaluable time, unwavering effort, and exceptional understanding, which significantly contributed to my academic achievements. Their extensive knowledge and plenty of experience have been a source of inspiration for me throughout my educational pursuits. Furthermore, I would like to thank Assistant Professor Dr. Noppakun Sangkhiew and Assistant Professor Dr. Pattarawet Tharawetcharak for their invaluable technical support during my research. I want to convey my appreciation to all individuals in the Industrial Engineering and Management faculty at Silpakorn University. The generosity and support of others have contributed significantly to my positive experience while studying and living in Thailand. In conclusion, I would like to express my gratitude to my parents. Their steadfast support over the past few years has enabled me to complete my studies successfully.

Jia MAO

TABLE OF CONTENTS

List of tables

Page

List of figures

Page

CHAPTER 1
INTRODUCTION

1.1 Motivation

Both practitioners and scholars note that construction projects are more susceptible to risks than other industries due to their inherent complexities. The identified risks can lead to decreased performance, higher expenses, delays in scheduling, and ultimately, failure of the project (Zou et al., 2017; Shishehgarkhaneh et al., 2024). Inadequate supply chain management (SCM) is a possible cause of the cost overruns and delays associated with the building sector. While supply chain management (SCM) is primarily associated with the manufacturing business, organizations in the construction industry can also get advantages by implementing similar best practices in certain operations (El-Sayegh, 2008). However, the construction business must still fully develop supply chain management (SCM). Although the construction industry has significant potential, the use of supply chain risk management (SCRM) principles, a sub-field of supply chain management (SCM), needs to be thoroughly investigated (Rudolf & Spinler, 2018).

In recent decades, a multitude of natural and anthropogenic catastrophes, including earthquakes, economic crises, war, terrorist attacks, and sanctions, have caused significant disruptions to supply chain activities. These disruptions are not isolated incidents but a growing trend. Coleman (2006) discovered substantial data indicating that the occurrence of anthropogenic disasters causing disruptions has been increasing significantly since the 20th century. The frequency and intensity of these disturbances have been reported to be on the rise. This trend underscores the inevitability of supply chain disruptions, making it clear that all supply chains are intrinsically dangerous (Segerstedt & Olofsson, 2010; Algahtany et al., 2016). This highlights the urgent need for proficiently handling risks in construction supply chains for the successful completion of building projects.

Over the past few decades, a substantial amount of knowledge has been accumulated regarding the field of SCRM. The studies in this text cover three main tasks of Supply Chain Risk Management (SCRM): risk identification, risk assessment, and risk mitigation. The authors cited in the text have researched these tasks and contributed to the understanding of SCRM. Both quantitative and qualitative methodologies have been used to explore these activities. However, to effectively reduce supply chain risks, it is necessary to comprehend how risks are formed, spread through interdependencies, and impact organizations' operations. Some researchers argue that most studies on Supply Chain Risk Management (SCRM) only focus on specific tasks, and there needs to be a comprehensive approach in the current literature that integrates these three tasks. This viewpoint is supported by Mills (2001), Micheli et al. (2008), and Qazi et al. (2015).

Risk identification work is crucial for the success of risk management efforts in the SCRM process (Neiger et al., 2009). Puljić (2010) argues that numerous factors, such as cognitive biases, influence managers' perception of supply chain risks. These factors might result in suboptimal decision-making. Hence, to enhance the accuracy and efficiency of the risk management model, it is essential to comprehend managers' perceptions of risks and integrate them into the decision-making process (Karamoozian & Wu, 2024).

This study uses the construction supply chain risk management (CSCRM) proposed by Shojaei & Haeri (2019), which is based on grounded theory. The framework consists of grounded theory, fuzzy cognitive mappings, grey relational analysis, and Shannon’s entropy. The sort of qualitative and quantitative analysis tools is being used systematically. The case study is a construction project in Kunming, China. The fuzzy cognitive mapping is being established effectively. The new CSCRM will be compared with similar research in the literature. The pros and cons will be identified.

1.2 Research Objectives

1. To apply a construction supply chain risk management method using the grey relational analysis method.

2. To apply the method on steel supplier selection, the case of a construction project in Kunming.

1.3 Research Contributions

1. A validation of new risk management method in construction supply chain risk management.

2. An analyze of opportunities and obstacles of using the new method in practice.

3. To bridge the project management between scholars and practitioners about the gap of supply chain risk management.

1.4 Scopes and Limitations

1. This study is a combination of survey research and quantitative research; however, the primary one is the quantitative research that attempts to apply a proposed framework in real-wold construction projects. However, it cannot guarantee to be used as a reference for other industries.

2. The data is collected from a case study between Mar 2024 to May 2024. Thus, the current situation of the business is a primary factor.

1.5 Acronyms

AEC	Architechtural, Engineering, and Construction
AI	Artificial Intellgence
CSCRM	Construction Supply Chain Risk Management
EPC	Engineering, Procurement, and Construction
FCM	Fuzzy Cognitive Mapping
GRA	Grey Relational Analysis
GT	Grounded Theory
SCM	Supply Chain Management
SCRMP	Supply Chain Risk Management Process

CHAPTER 2

LITERATURE REVIEW

This chapter reviews supply chain risk concepts. Its general idea and a specific construction supply chain risk management (CSCRM) are examined in section 2.1. Furthermore, section 2.2 concisely investigates the concepts of the supply chain risk management process (SCRMP) to draw the whole picture of the research area. Section 2.3 reviews three selected analysis tools used in this research. It follows the guidance of Shejaei et al. (2019). The selected previous reports are briefly reviewed in section 2.4. Finally, the conclusion of this chapter is drawn in section 2.5.

2.1 Supply Chain Risk

A supply chain refers to the interconnected system of individuals, businesses, materials, operations, and technology collaborating to produce and distribute a product or service. It encompasses the entire process, starting from transporting raw materials to the factory and concluding with delivering the final product to the client (Lutkevich, n.d.).

Supply chain management (SCM) emerged in the manufacturing sector throughout the 1980s, signifying a fundamental change in how corporations conducted their logistics and material management and it was used to improve the efficiency and effectiveness of the supply chain (Cooper et al., 1997). In recent years, the scope of SCM has broadened to encompass several sectors, including retailing, medical service, food services, and service sectors. Supply Chain Management (SCM) is widely recognized as an essential business strategy for firms to maintain their competitiveness in the global economy (Shishehgarkhaneh et al., 2024).

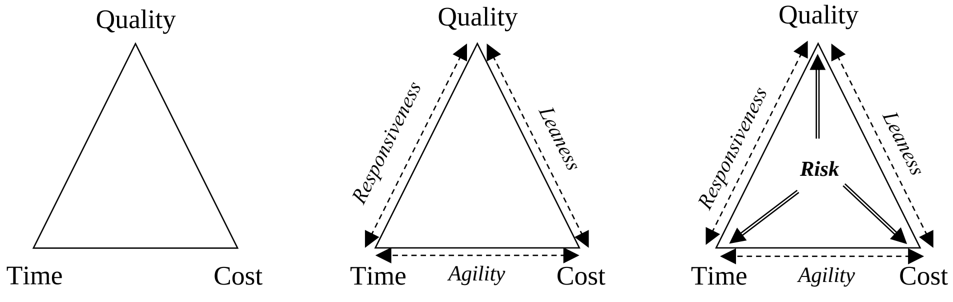
2.1.1 Supply chain risk management

Supply chain risk management (SCRM) refers to systematically identifying and mitigating any weaknesses or vulnerabilities within a company's supply chain. The objective of SCRM is to mitigate the adverse effects of these risks on a company's operations, reputation, and financial performance (IBM, n.d.).

Product competition often occurs between rival supply chains rather than inside individual organizations. The significance of risk in the supply chain is escalating due to several factors: unpredictability in supply and demand, the global expansion of the market, decreasing product and technology life cycles, and the growing reliance on outsourcing (Micheli et al., 2008).

The focus of supply chain management has to shift towards supply chain risk management (SCRM). Supply chain management has evolved to encompass responsiveness, leanness, and agility. These three factors contribute to a rise in the complexity of the supply chain and a shift in focus towards risk, see Fig. 2.1.

Managing risks in a supply chain is challenging due to three main factors: the complex interdependencies that make it hard to identify risks, the possibility of risks occurring at any level of the supply chain, and the lack of well-established tools and techniques for supply chain risk management, resulting in a primarily improvised approach.



Traditional SC Millennium SC Moder SC

Figure 2.1 Supply chain management focusing.
Source: Norrman and Janson (2004)

Tang (2006) categorizes four fundamental strategies to alleviate the consequences of supply chain risks:

1) Demand management: the act of coordinating with partners downstream to influence demand in a favorable way.

2) Product management: the process of making changes to the design of a product or its manufacturing process in order to improve the flow of materials in the supply chain.

3) Information management: the coordination and collaboration among partners in the supply chain through the sharing of information.

4) Supply management: working with partners further up the supply chain to ensure the efficient and adequate supply of materials.

The importance of supply management is heightened as firms become increasingly reliant on suppliers, leaving them vulnerable to supply hazards. Just as project risk management is crucial, SRM is now being integrated into supply management to reduce the risks associated with the supply chain.

2.1.2 Construciton supply chain risk management (CSCRM)

The construction industry is crucial in stimulating the global economy. Its significant influence on the physical infrastructure and its ability to generate abundant job prospects for both skilled and unskilled workers while promoting economic development is widely acknowledged. Moreover, construction projects commonly exhibit a hybrid characteristic, as they need the utilization of manufactured commodities and vital resources such as raw materials and energy (Bao et al., 2020). The client's satisfaction defines the quality of a construction project. In contrast, the project's success depends significantly on the performance of the project team. The construction supply chain is defined as a sequence of activities that convert raw materials into finished products (such as roads or buildings) and services (such as design or budgeting) for a client, regardless of organizational boundaries.

Moreover, as stated by Larson (2001), CSCM involves managing information, flow, and financial issues during the development of a building project. Hatmoko and Scott (2014) defined CSCM as a cooperative system encompassing suppliers, contractors, clients, and their representatives. The goal is to synchronize the installation and exploitation of information to provide resources for building projects, such as supplies, equipment, labor, and temporary works. The notion of CSCM has the potential to significantly improve the value for clients and stakeholders by strategically prioritizing profitability. Moreover, the main objective of overseeing a construction supply chain (CSC) is to strategize and supervise the required quantities of components to be transported to where the final assembly occurs.

Moreover, as depicted in Fig. 2.2, the construction business involves many players, including contractors, sub-contractors, designers, consultants, and suppliers. The contractor frequently employs multiple sub-contractors to meet diverse needs in the construction project. These sub-contractors may have expertise in supplying materials, machinery, skilled workers, unskilled workers, or any other unique need that may develop during the project.

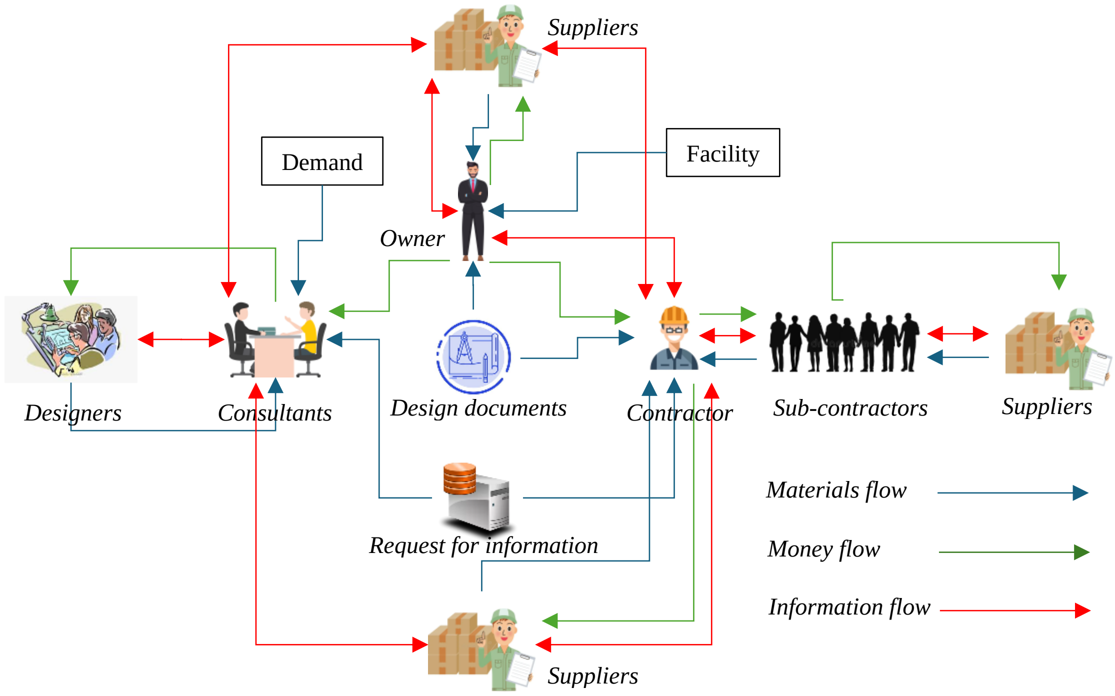


Figure 2.2 Construction chain network.
Adopted from: Shishehgarkhaneh et al. (2024)

Consequently, the contractor industry has many sizes, from small business owners to large multinational enterprises. Therefore, the supply chain in the construction sector is distinct from that in manufacturing and is characterized by more complexity and unpredictability. The implementation of Supply Chain Management (SCM) in construction projects is challenging due to specific project characteristics, such as the temporary involvement of multiple organizations (Young et al., 2011), short-term adversarial relationships, and difficulties in managing networks that involve multiple stakeholders, supply of materials and components, and various services (Abdulla & Nasir, 2017).

2.2 Supply Chain Risk Management Process (SCRMP)

Figure 2.3 illustrates the entire SCRMP. Although this paper primarily emphasizes providing a thorough explanation of the three phases, it is important not to overlook the other elements, including drivers, risk categories, supplier/logistics evaluation criteria, and performance measures (Kersten et al., 2011). Phase I of the SCRMP consists of risk identification, risk measurement, and risk assessment, which will be explained in the following section. The input for this initial phase consists of both internal and external factors, as depicted in Fig. 2.3.

2.2.1 SCRMP Phase I

1) Risk identification

Risk identification is a thorough and organized assessment of potential supply chain risks linked to the specified issue. The risk categories have been incorporated into our comprehensive framework (Fig. 2.3). Instead of aiming to include every possible risk, this list serves as a representative example of the numerous risks that could exist. It is essential to identify the regions that have been affected and fully understand the repercussions in order to execute policies to reduce the risks effectively.

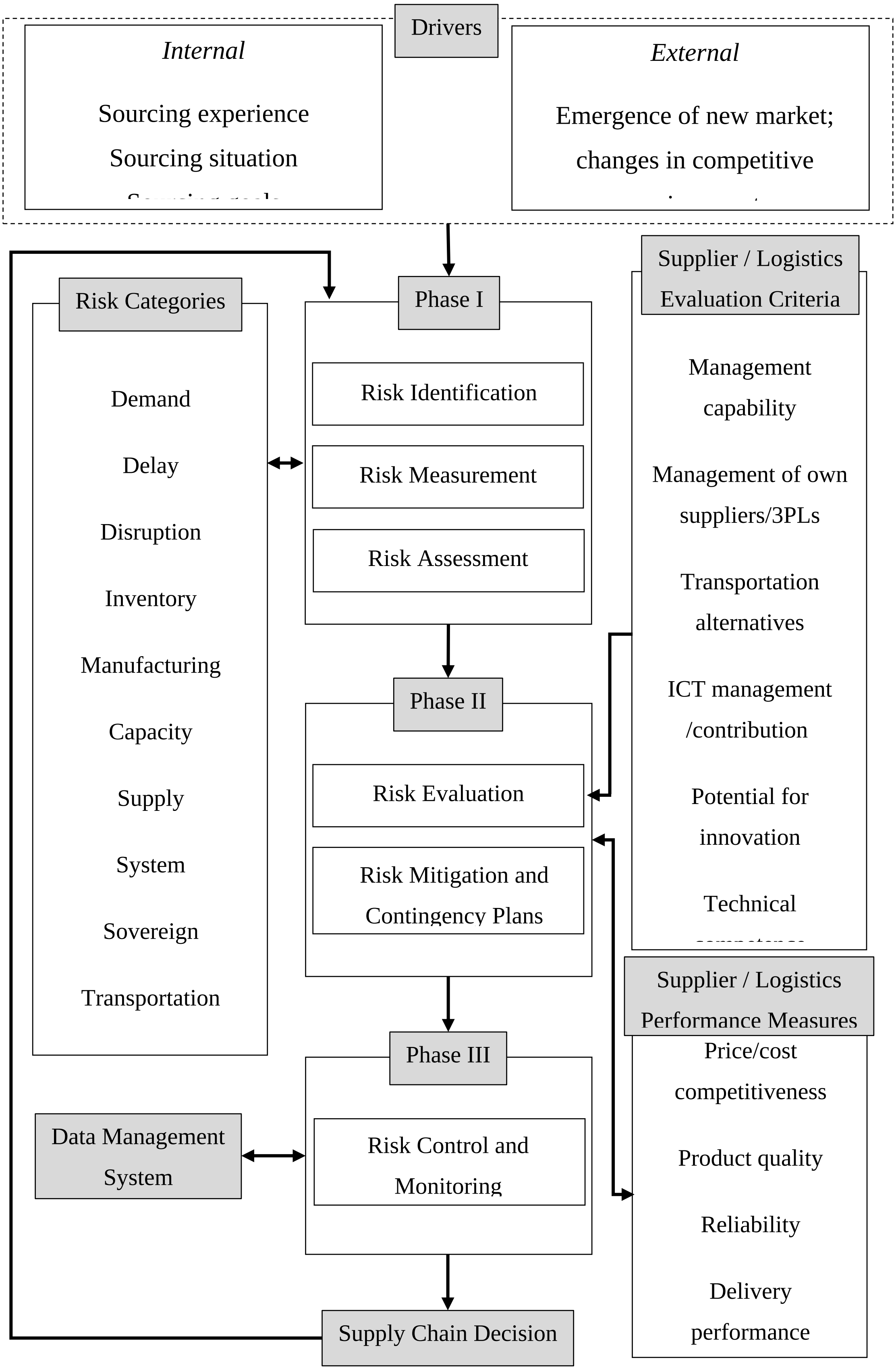


Figure 2.3 Supply chain risk management process.

2) Risk measurement

Risk measurement, the second stage of the initial phase (Fig. 2.3), entails assessing the potential repercussions of all supply chain risks, together with their respective magnitudes of impact. Consequences refer to the way in which a danger shows its consequences on resources, either in terms of manner or extent. Possible outcomes can encompass the loss or impairment of assets, income reduction, disruption of service levels, exceeding budgeted expenditures, delays in project timelines, subpar process efficiency, liabilities acquired, expenses for repairing damages, or occurrences of injuries. By utilizing a checklist, event tree, fault tree, FMEA, or Ishikawa CEA analysis, it is possible to discover risks related to SC (Ho et al., 2015). Once these risks are identified, the relevant consequences and their severity levels may be evaluated.

3) Risk assessment

Risk assessment, which is the third step of the initial phase (Fig. 2.3), is essentially the evaluation of uncertainties. It involves determining the probability of each risk element. Objective information can be used to analyze uncertainties and probability distributions can be constructed for relevant supply chain risks or outcomes. If objective information is lacking, subjective information, beliefs, and judgment can be employed to estimate distributions. Methods such as the Delphi method or expert focus groups can assist in the determination of probabilities. Additional methodologies encompass parameter estimation, five-point estimation, probability encoding, and Monte Carlo simulation. Alternatively, one can apply probability categories as recommended in the US Military Standard 882C.

2.2.2 SCRMP Phase II

The second phase of the SCRMP include the processes of assessing and addressing risks, as well as developing contingency plans. Both of these processes rely on evaluation criteria and performance measures for suppliers and logistics, as seen by the boxes on the right-hand side of Figure 2.3. Although the current work does not include a discussion of these criteria and metrics, they play a significant role in the two processes discussed below.'

1) Risk evaluation

The initial stage of Phase II in the SCRMP is risk assessment, which comprises the sub-stages of risk prioritization and risk approval. These two sub-steps are particularly useful when it is challenging to estimate objective probabilities or when there is a lack of sufficient data to calculate probabilities. The following components are discussed (Norrman & Lindroth, 2004).

Risk ranking: Risk ranking is the product of risk consequence index and risk probability index.

Risk acceptance: After classifying the hazards associated with the SC (Supply Chain), it is necessary to set acceptable levels of risk. It is the second sub-step of risk evaluation in Phase II. The ALARP (as low as reasonably practicable) approach can be employed to categorize a safety-critical event's risk as unacceptable, bearable, or acceptable. The establishment of these criteria necessitates the involvement of cross-functional teams, including senior management, and the utilization of all pertinent information that is accessible. The demarcation between acceptable and unacceptable supply chain risks can be defined based on these criteria, as depicted in Fig. 2.4.

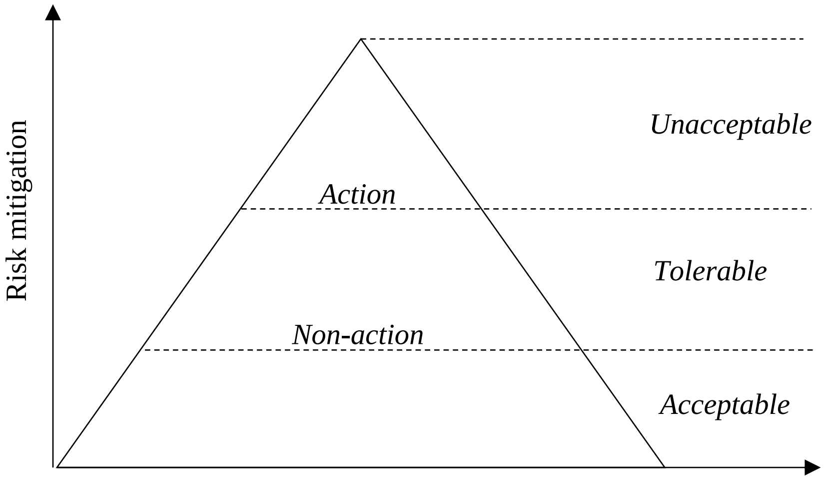


Figure 2.4 Risk acceptance level.

Source: Tummala and Schoenherr (2011)

2) Risk mitigation and contingency plans

The risk mitigation and contingency plans component, the second part of Phase II, entails formulating risk response action plans to manage and regulate the risks (risk planning). The hazard totem pole (HTP) study is an effective evaluation technique that can provide valuable insights in this context. The following technique is reiterated here to emphasize its relevance in the supply chain setting. The technique is valuable because it effectively combines risk factors outlined earlier, specifically the severity and probability of the consequences.

2.2.3 SCRMP Phase III

During the final stage of the SCRMP, which is risk control and monitoring, it is possible to assess the progress made in relation to the risk response action plans that have been put into place. If there are any deviations from the expected supply chain performance, corrective actions can be performed. This corresponds to Phase III, as seen in Figure 2.3. The procedure serves as a method to identify potential preventative actions and offer recommendations for further enhancement. Reports are made for deviations from desired outcomes, aberrant instances, and disturbances to the supply chain.

Data management systems can assist in this endeavor through a modular structure that includes a catalog of identified supply chain risk factors, severity levels of consequences, probabilities of risks, hazard totem pole analysis, government regulations and policies, tariffs and customs policies, transport schedules and triggers for supply chain risks (Tang, 2006). Relevant risk information can be maintained and updated as required. It can be utilized not only for efficient surveillance and implementation of necessary measures but also for ongoing enhancement of risk evaluation and control. Although the mentioned system may be adequate, there are also other advanced providers of supply chain risk management software that offer commercial solutions, including Software as a Service (SaaS) options specifically designed for risk management.

A supply chain decision can be determined based on the behavior exhibited during these three stages. However, like many other business procedures, the exercise does not conclude at this point. Management must consistently emphasize the Strategic Change and Risk Management Plan (SCRMP) in order to adapt to any modifications that have taken place in the environment (Finch, 2004). Risk tolerances, preventative costs, and severity levels may all undergo changes. Hence, it is imperative to implement a consistent monitoring and evaluation system.

2.3 Selected Risk Analysis Techniques

There are several risk analysis techniques in the literature. However, we reviewed some analysis tools that are scarce in the literature. Please note that no one guarantees which tool is the most suitable for all risk analysis cases.

2.3.1 Grounded theory

Grounded Theory (GT) is a methodical approach to qualitative research developed by Glaser and Strauss in 1967 (Charmaz, 2000). Glaser and Strauss (2017) described it as a method for developing a well-suited theory for its intended purposes. Abstracting concepts and their interrelationships derive grounded theory (GT) from qualitative data analysis, such as interview transcripts. There are three methods for implementing GT, which are as follows: 1) Straussian approach, 2) Glaserian approach, 3) Constructive approach.

Grounded theory (GT) is a research methodology focused on developing a theory based on data collected and analyzed methodically. It is employed to reveal social processes encompassing social ties and collective behaviors. The study 'Awareness of Dying' was conducted in California, USA, by Glaser and Strauss, who were responsible for its development. It is a comprehensive approach to theory development that relies on collecting and analyzing systematically obtained evidence (Noble & Mitchell, 2016). The steps of Grouded theory analysis are shown in Fig. 2.5.

The coding step is the most important. It comprises two techniques: open and axial codings.

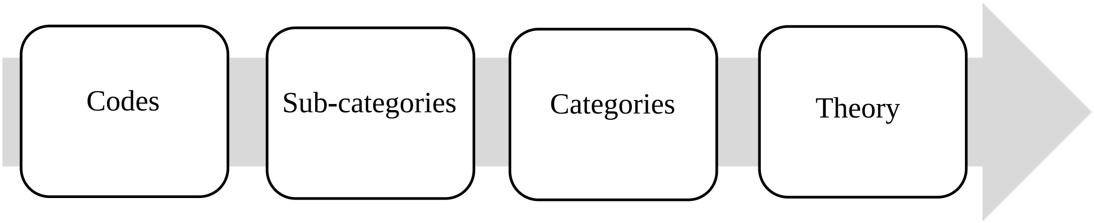


Figure 2.5 Grounded theory steps.

Source: Noble and Mitchell (2016)

Open Coding is an analytical procedure where data is analyzed line by line to identify concepts and uncover their attributes and dimensions. Additionally, categories have been identified to contain all items, events, or actions/interactions that are connected to the research topic (such as supply chain risks) and will be coded. When categories are established, a comparison of their members reveals that all classed items (things, events, or actions/interactions) exhibit variations in terms of their qualities and dimensions. Consequently, they will be categorized as subcategories, which is the ultimate result of this stage (Turner & Astin, 2021).

Axial coding involves establishing the relationship between categories and their sub-categories based on their qualities and dimensions. This process aims to create a more exact and comprehensive explanation of the phenomenon under study. Axial coding is the term used to describe the procedure that occurs around the axis of a category. At this level, researchers aim to comprehend the explanations for "How?" and "Why?" by situating the phenomena within its contextual framework (structure) and by identifying the sequence of actions/interactions throughout time in response to specific challenges and difficulties (process) (Turner & Astin, 2021). By examining both the structure and process, the following information will be obtained:

1) Causal conditions (*C*)
2) Intervening conditions (*I*)
3) Contextual conditions (*G*)
4) Actions/Interactions (Strategies) (*S*)
5) Consequences (*O*)

Concepts will be categorized into the five classifications above. The many ideas are structured around a central set of ideas, representing the primary occurrence (i.e., supply chain hazards). However, the names of these groups are relatively self-explanatory (Manuj & Pohlen, 2012).

2.3.2 Fuzzy congnitive map

A cognitive map is a mental model that helps individuals acquire, encode, store, retrieve, and interpret information about things' relative positions and characteristics in their everyday or metaphorical spatial surroundings. Edward Tolman introduced the notion in 1948 (Shokouhyar et al., 2019). He attempted to elucidate the behavior of rats that seemed to acquire knowledge about the spatial arrangement of a maze, and later, this concept was extended to other creatures, including humans. Subsequently, academics, particularly in the domain of operations research, expanded the word to encompass a semantic network that represents an individual's own knowledge or schemas (Zheng, 2024).

A cognitive map visually represents an individual's understanding of the spatial and environmental relationships within a geographic area. An illustrative depiction of the path connecting two places, such as a sketch map, is a tangible manifestation of the cartographer's cognitive understanding of the spatial layout. A cognitive map refers to a mental representation of geographic knowledge. Although it is often used metaphorically, it signifies those individuals and animal possess and utilize this knowledge to navigate, make spatial decisions, and influence their spatial behavior. This includes selecting routes, destinations, places to live, and other related choices. There is ongoing discussion regarding the nature of cognitive map knowledge, including whether it primarily consists of imagery and representations or other types of knowledge. Additionally, there is debate about how cognitive maps encode spatial relations, such as distance, scale, and direction, and how they connect spatial and nonspatial information. Furthermore, researchers are interested in understanding how cognitive maps are mentally organized and stored and how cognitive, neurological, and external factors influence them (Kitchin & Freundschuh, 2018).

Kosko (1992) presented fuzzy cognitive maps (FCMs) as a way to enhance cognitive maps by allowing the incorporation of fuzzy causal linkages instead of strictly precise ones. FCM is a digraph that is both signed and fuzzy, with weights assigned to its edges. Nodes symbolize ideas or principles, whereas edges demonstrate the intensity, polarity, and orientation of cause-and-effect connections. FCM, a well-established artificial intelligence technique, combines concepts from artificial neural networks and fuzzy sets. Fuzzy Cognitive Maps (FCMs) are employed to assess the impacts of various techniques in relation to the attainment of specific objectives. Fuzzy Cognitive Maps (FCMs) have been utilized across a range of fields, such as business, control systems, medicine, robotics, environmental science, and information technology. Within the realm of business, FCMs have been employed for various objectives, including planning, management, decision-making, modeling, prediction, and decision support systems (DSSs). The development of FCM in this work is grounded in the retrieved notions from grounded theory. Each of those concepts will function as its own node within the FCM graph (Schuerkamp & Giabbanelli, 2023).

1) Fuzzy cognitive map basis

Fuzzy Cognitive Maps (FCMs) are a representation of human tacit knowledge. They consist of a network of interconnected nodes, each representing a notion and associated with a variable. Fuzzy Cognitive Maps (FCMs) are complex systems that incorporate feedback mechanisms, enabling the impact of a change in one node to spread across the entire system and influence the initial node. Directed edges in FCMs express the influence of a cause idea on an effect concept. The intensity of each edge is denoted as w_{ij}, where i is the cause node, and j is the effect node. Figure 2.6 depicts a sample of FCMs, with A representing its adjacency matrix according to Eq. (2.1).

$$A = \begin{pmatrix} 0 & w_{12} & w_{13} & 0 \\ 0 & 0 & w_{23} & 0 \\ w_{31} & 0 & 0 & w_{34} \\ w_{41} & 0 & w_{43} & 0 \end{pmatrix} \tag{2.1}$$

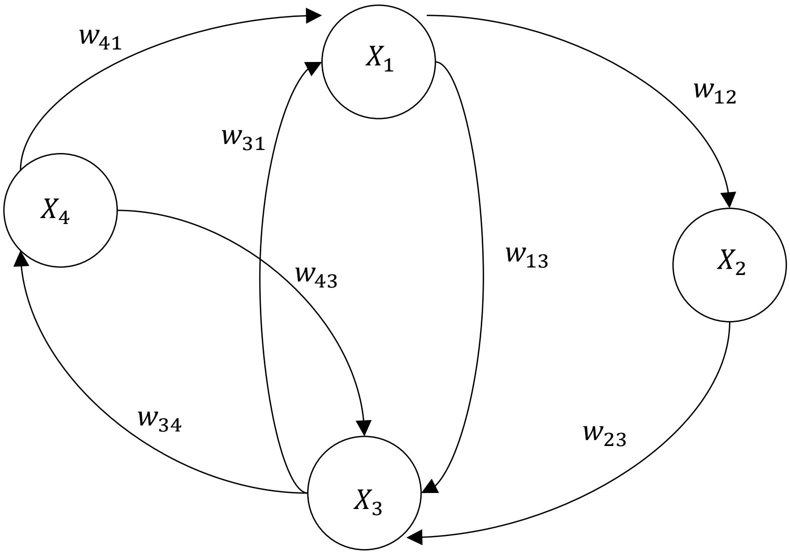


Figure 2.6 A fuzzy cognitive map.

The dynamics of FCM start with the initial vector state $\vec{C}_0$, that represents a proposed initial impluses. The vector is described as:

$$\vec{C}_0 = (C_0^1\ C_0^2\ C_0^3 \ldots C_0^n) \tag{2.2}$$

An iterative inference procedure is used to compute each node's updated value. This approach utilizes an activation function that transforms the nodes' values into a normalized range of either $[0, +1]$ or $[1, +1]$. Furthermore, Eq. (2.3) is utilized to compute every node's revised value (Poczeta et al., 2020).

$$C_j^t = f\left(C_j^t + \sum_{i=1, j\neq i}^{N} (w_{ij} \times C_i^t) \right) \tag{2.3}$$

Several activation functions have been suggested in the literature, such as the bivalent, trivalent, unipolar sigmoid (logistic), and hyperbolic tangent functions. The unipolar sigmoid activation function is commonly utilized when conceptual values are mapped in the range $[0, +1]$ (Papageorgiou & Salmeron, 2012). Alternatively, if the values of the ideas are within the range of $[1, +1]$, the hyperbolic tangent activation function is employed. Given that the values of the nodes fall within the range of $[1, +1]$, the hyperbolic tangent activation function is employed in the following manner:

$$f(x) = \tanh(x) \tag{2.4}$$

During the inference process, the system will change, and there will be three potential outcomes for the stable vector state. These outcomes illustrate how the initial vector state affects the state of each FCM node (Salmeron & Papageorgiou, 2012). The following are the conditions: i) fixed-point attractor, ii) limit cycle, iii) chaoric attractor.

2) Fuzzy cognitive mapping procedure

There are typically two primary methods for developing and constructing FCMs: expert-based approaches (deductive modeling) and computational methods. The expert-based method is dependent exclusively on human expertise and domain knowledge. Nevertheless, the computational method utilizes existing data and a learning algorithm to create or facilitate the construction of an FCM model for a specific system. This research employs an expert-based method. The expert-based method proceeds through three stages as follows:

Stage 1: Significant concept identification.

Stage 2: Causal relationship building indentification.

Stage 3: Causal relationship strength estimation.

A panel of specialists is employed to carry out the three stages above. Each expert assesses the causality (causal link) level between nodes by employing language characteristics, such as solid influence, moderate impact, and weak influence. It involves soliciting experts' opinions on the relative intensities of concepts using linguistic characteristics, as outlined in Table 2.1. The values are subsequently defuzzified using the center of gravity (COG) approach (Bakhtavar et al., 2021).

Table 2.1 Causal relationships and crisp variables.

Crisp variable	Fuzzy number
Very strong negative (-4)	$(-1, -1, -0.75)$
Stong negative (-3)	$(-1, -0.75, -0.5)$
Medium negative (-2)	$(-0.75, -0.5, -0.25)$
Weak negative (-1)	$(-0.5, -0.25, 0)$
Neutral (0)	$(-0.25, 0, 0.25)$
Weak positive (+1)	$(0, 0.25, 0.5)$
Medium positive (+2)	$(0.25, 0.5, 0.75)$
Strong positive (+3)	$(0.5, 0.75, 1)$
Very strong positive (+4)	$(0.75, 1, 1)$

It is essential to merge multiple maps into one when developing expert-based FCMs, as each expert may generate a unique FCM. Various strategies have been suggested to tackle this problem, including the Delphi technique. The Delphi method aims to achieve agreement among experts by repeatedly seeking their input and allowing them to revise their conclusions. However, the augmented technique does not necessitate specialists to alter their assessments. The augmented adjacency matrix is constructed by summing the adjacency matrix of each expert.

Two fuzzy cognitive maps are FCM_x and FCM_y are mutually exclusive and, $C^{[x_i]}$ and $C^{[y_i]}$ are their elements, respectively. Let $w_{i \to j}^{x}$ is the adjacent matrix of

FCM_x; likewise, the adjacent matrix of FCM_y is $w_{i\to j}^{y}$. Thus, the augmented adjacent matrix is (Poczeta et al., 2020):

$$Adj_{AU} = \begin{pmatrix} w_{i\to j}^{x} & 0 \\ 0 & w_{i\to j}^{y} \end{pmatrix} \tag{2.5}$$

However, if the common elements exist, then the element $w_{i\to j}^{Au}$ in the augmented matrix is determined as:

$$w_{i\to j}^{Au} = \frac{\sum_{i=1}^{n} w_{i\to j}^{k}}{n} \tag{2.6}$$

where n is the FCMs added quantity, k is the FCM label, and i and j are the relationship identifiers.

2.3.3 Grey relational analysis

Professor Julong Deng's paper titled "The Control Problems of Grey Systems" was published in the Systems and Control Letters journal in 1982, making it the first study on grey systems to be published in that magazine (Liu et al., 2017). In the same year, Professor Deng published a paper titled “Grey Control System” in Chinese, which was subsequently published by the Journal of Huazhong University of Science and Technology. The release of these two influential works signified the emergence of a novel and interdisciplinary field known as gray system theory.

The Grey Relational Analysis (GRA) can solve complex problems involving complicated connections between components and variables. The GRA method has been widely employed to address issues related to ambiguity in situations involving discrete data and incomplete information (Ertuğrul et al., 2016). This method initially converts the performances of each alternative into comparability sequences using a mechanism similar to normalization. Then, an optimal or benchmark sequence is established, which will then be employed to compute the gray relational coefficient among all comparable sequences and the benchmark sequence. Finally, the grey relational degree between each comparability sequence and the reference sequence is calculated using the obtained grey relational coefficients, and the alternatives are ranked accordingly. This technique is executed by following a series of steps (Rajesh & Ravi, 2015):

Step 1: Decision-making matrix construction.

A decision-making matrix is constructed based on the experts' sentiments. Suppose there are m alternative characterized with n criteria as follows:

$$G = \begin{bmatrix} G_{11} & G_{12} & \dots & G_{1n} \\ G_{21} & G_{22} & \dots & G_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ G_{m1} & G_{m2} & \dots & G_{mn} \end{bmatrix} \tag{2.7}$$

where G_{ij} is the performance of choice i corresponding to criterion j.

Step 2: Performance value normalization.

Alternatives' performance values are normalized and combined into a comparability sequence $Y_i = (y_{i1}, y_{i2}, y_{i3}, \dots, y_{in})$. The larger-the-better criteria and the smaller-the-better criteria are calculated using Eqs. (2.8) and (2.9), respectively.

$$y_{ij} = \frac{G_{ij} - Min\{G_{ij}, i = 1,2, \dots, m\}}{Max\{G_{ij}, i = 1,2, \dots, m\} - Min\{G_{ij}, i = 1,2, \dots, m\}} \tag{2.8}$$

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

$$y_{ij} = \frac{Max\{G_{ij}, i = 1,2, \dots, m\} - G_{ij}}{Max\{G_{ij}, i = 1,2, \dots, m\} - Min\{G_{ij}, i = 1,2, \dots, m\}} \tag{2.9}$$

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

However, since the risk analysis tends to find the lowest risk, all criteria are considered the smaller-the-better criteria.

Step 3: Reference sequence definition.

The definition of reference sequence is constructed in this step. The comparability sequence from the last step will be compared using Eq. (2.10).

$$y^0 = (y_1^0, y_2^0, \dots, y_n^0) \tag{2.10}$$

$$= \left(\max_{i=1\to m} y_{i1}, \max_{i=1\to m} y_{i2}, \max_{i=1\to m} y_{i3}, \dots, \max_{i=1\to m} y_{in} \right)$$

where y^0 is the target value related to the criterion j, and y_{ij} are the values from the normalized matrix from step 2.

Step 4: Grey relational coefficient calculation.

The coefficient is calculated using Eq. (2.11). It indicates that how close are the values of y_{ij} to the target sequence y^0.

$$\alpha\left(y^0, y_{ij}\right) = \frac{\Delta_{min} + \delta\Delta_{max}}{\Delta_{\mathrm{ij}} + \delta\Delta_{max}}, \ \ \forall i \in \{1,2,..,m\}; j \in \{1,2,\dots,n\} \qquad (2.11)$$

where $\alpha(y^0, y_{ij})$ is the grey relational coefficient between y^0 and y_{ij}, and $\Delta_{ij} = |y^0 - y_{ij}|$, $\Delta_{min} = \min\{\Delta_{ij}, \forall i \in \{1,2,..,m\}; \forall j \in \{1,2,..,n\}\}$, $\Delta_{max} = \max\{\Delta_{ij}, \forall i \in \{1,2,..,m\}; \forall j \in \{1,2,..,n\}\}$, and δ is the distinguishing coefficient. Please note that $\delta \in [0,1]$.

The δ's value shows the important of minimum scores corresponding to the maximum score. It is a pre-determine parameter which defined by the decision maker.

Step 5: Grey relational degree calculation.

Then, the grey relational degree is computed as:

$$\Psi(y^0, y_i) = \sum_{j=1}^{n} w_j \alpha(y^0, y_i), \ \ \forall i \in \{1,2,..,m\} \qquad (2.12)$$

where $\Psi(y^0, y_i)$ is the grey relational degree between y_0 and y_i. It reflects to the correlationship degree between the target sequence and the comparability sequence. w_j is the criterion weight j, and $\sum_{j=1}^{n} w_j = 1$.

As a result, the higher the grey relational degree, the closer to the target sequence it is. Accordingly, the alternative with the highest grey relational degree is the best in the system.

2.4 Previous Works

Rudolf and Spinler (2018) investigated risk factors in large-scale construction projects, specifically in the supply chain process. They focused on engineering, procurement, and construction (EPC) projects. The supply chain risk management (SCRM) concept was used to lead the study's taxonomy. The study started with a literature examination with initial risk taxonomies. It comprises environment, supply chain coordination, management, supplier, and behavior and cooperation factors. Then, the taxonomy was validated using the SCRM framework. Finally, the expert survey was used in the study to make the result generally. The results showed that the five most frequently named as the significant risks are ‘no mindset of pain/gain sharing,’ ‘mutual commitment to project success,’ ‘performance and operations,’ ‘collaboration and teaming,’ and ‘scope and baseline specification.’ Interestingly, three of them were in the behavior and cooperation class. It implies that no matter what the industry is, collaboration in the supply chain is the most essential part of supply chain management.

Shojaei and Haeri’s (2019) study is the mainstream of our research. Supply chain risk management has been effectively applied to the manufacturing industry. However, it was disregarded in the construction industry, specifically in large-scale construction projects. Most managers relied on their experience. The authors closed the gap using management’s experience with scientific analytical tools. The construction industry’s inclusive supply chain risk management included three analytical tools: grounded theory, fuzzy cognitive mapping, and grey relational analysis. A real case was used to describe the performance of the proposed approach. Five senior managers were the experts in their case study. The interviews were the first step, and grounded theory was applied systematically. A fuzzy cognitive map was constructed. Finally, the grey relational analysis ranked the risk factors and recommended appropriate risk mitigation simultaneously. The results showed that the proposed method is able to capture the specialists’ perceptions better than similar approaches in the literature. Moreover, their approach was an effective and time efficient manner.

Sugathadasa et al. (2021) stated that small-sized construction companies have faced more risks and disruptions during construction phases more than large-sized construction companies even their systems are less complex than large-sized projects. Furhtermore, the risk characteristics are different and unique. The authors tried to idenfity and quantify the risks to offer appropriate risk mitigation approaches. The risks in the study corresponded to time, cost, and quality dimensions. Each dimension was divided into two groups: supply, and operation. The time-supply risks included material delay, defective materials, improper machines, and equipment use. The time-operation risks included project delay and substandard working conditions. The cost-supply risk included defective materials. The cost-operation risk included project delay, substandard working conditions, and poor planning and scheduling. The quality-supply risk included supplier selection and defective material. The quality-operation risk included project delay and project failure. The study method consisted of three significant steps: risk identification, expert interviews, data collection, editing, and mitigation strategy suggestion. The case study revealed that small-sized construction projects are suitable for straightforward risk assessment and management because they consume fewer management resources and yield reasonable results.

Karamoozian and Wu (2024) observed a severe impact of the COVID-19 pandemic on the construction industry. The risk has been ignored for decades, and no one has considered it. The researchers applied fuzzy theory to reflect the fuzzy environment of the construction industry during the pandemic. The technique for order preference by similarity to the ideal solution (TOPSIS) was incorporated with fuzzy theory, called FTOPSIS. Furthermore, the researchers also employed DEMATEL to identify the correlation between risks. The expert survey was conducted using the Delphi method to point out the supply chain risk factor in the construction industry. Twelve respondents participated in this research with three rounds of interviewing: risk point out, score assigning, and concurrence. The findings disclosed that material and financial supplies were the most significant risk factors. They also illustrated the risk mitigation strategies and construction supply chain redesigning.

Chen et al. (2024) designed construction supply chain resilience (CSCR) in the context of construction material management. Resilience implies how well a supply chain can survive and recover from disruptions. The research questions were 1) the difference between secondary sourcing and back-ordering regarding cost-effectiveness and 2) the supply chain inventory cost and effective management. A mathematical model that reflects robust optimization was formulated. The researchers also found the sensitivity analysis interesting. A numerical example was generated, and the model was tested using a CPLEX optimizer. The results revealed that secondary sourcing and back-ordering strategies could alleviate the impact of disruption. Additionally, secondary sourcing, precisely material and transportation costs, burdened the company more than the back-ordering strategy. The primary contribution of this study was the quantitative analysis of the construction supply chain, which can be applied straightforwardly in construction companies.

2.5 Conclusion

This chapter examined the foundations of supply chain risk management. We started by reviewing supply chain management and its evolution. The literature showed that modern supply chain management focuses not only on time, quality, and cost but also on risk management. Supply chain risk management was reassessed. Additionally, the context of construction supply chain risk management was examined rigorously.

Due to the complexity of the construction supply chain, which includes various stakeholders, multi-echelons of participants, and assorted flows, the identification, evaluation, and mitigation of risk are not simple. On the other hand, a fancy risk management tool is not appropriate in real industry. It could not be in the hands of all parties in the company, contractors, and sub-contractors. Thus, the construction supply chain risk management is still under investigation to compromise between academic and real industry.

We explored the grounded theory, fuzzy cognitive maps, and grey relational analysis backgrounds. A series of tools will be employed in this research project. They look cumbersome; however, they are reasonable and unambiguous. The grounded theory yields three-hundred-and-sixty-degree risk factors in construction supply chain management. The fuzzy cognitive maps return the graphical relation among risk factors. Since the risk factors may affect each other, the fuzzy cognitive maps facilitate our understanding of the phenomenon. Lastly, the grey relational analysis gives us the weight of each risk factor. Furthermore, we could consider risk mitigate simultaneously.

CHAPTER 3

RESEARCH METHODOLOGY

This chapter presents the research process used in this study.

3.1 Sample Construction Project

The selected construction company is listed in the stock market. Unfortunately, the company details are confidential. We can interview fifteen company experts in supply chain management, but the respondent information is confidential. The interview has two stages. The first stage asks about the risk factors in construction supply chain management. The data will be compared to the initial risk factors that we generated from the literature. The second interview asks about the score of risk factors, its impact, and risk mitigation strategies. The second interview asked about the score of the performance of each supplier: local (A1 and A2), regional (B1 and B2), and international (C) suppliers—there were five suppliers—on criteria by giving a five-point Likert scale: score 1, 2, 3, 4, and 5 means deficient, low, fair, reasonable, excellent performance corresponding that criterion, respectively. The data will be analyzed using the GRA technique. The data will be analyzed using the tool series.

3.2 Research Procedure

The procedure is shown in Fig. 3.1.

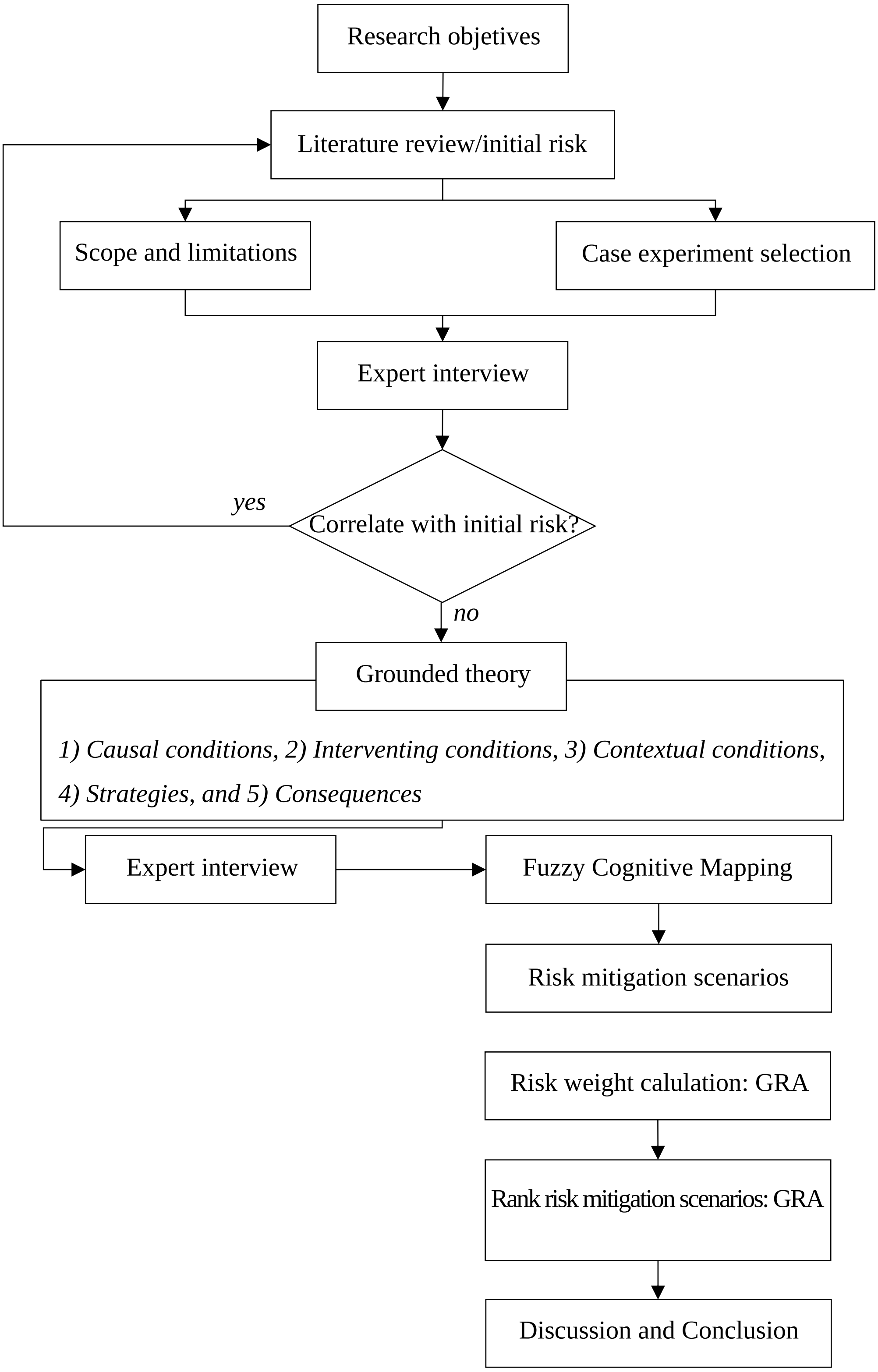


Figure 3.1 Research procedure.

3.3 Supply Chain Risk Factors

The supply chain risk factors in construction projects were retrieved from the literature that are Rudolf and Spinler (2018), Shojaei et al. (2019), Karamoozian and Wu (2024), and Shishehgarkhaneh et al. (2024). Then, five decision-makers, including the site manager, material control supervisors, purchasing manager, site engineers, and site supervisors, validated the proposed factors in a sample construction project. Eventually, this study found three main risk factors and fourteen sub-risk factors. The risk factors are shown in Table 3.1.

Table 3.1 Supply chain risk factors in construction projects.

Main risk factors	**Sub-risk factors**	**Code**
Critical time risk factors	Material delays due to no appropriate communication	R1
	Delay due to material condition and wastages such as weather impacts.	R2
	Machines and equipment are not ready to be used due to lack of maintenance.	R3
	Project delays due to environment effects.	R4
	Deficit of workforce due to workforce market and labor’s absenteeism	R5
Critical cost risk factors	Loss due to material condition and wastages such as weather impacts.	R6
	Project delays due to environmental impacts.	R7
	Overtime cost due to workforce deficit.	R8
	Improper planning and scheduling due to defective estimation.	R9
Critical quality risk factors	Incorrect selection of supplier because not knowing the right type of supplier to order.	R10
	Material defects due to weather impacts.	R11
	Project delays due to environmental impact to material quality.	R13
	Project failures due to poor engineering techniques.	R14

3.4 Resarch Instrument

A questionnaire was designed using risk factors and alternatives from section 4.2, see Appendix A. However, in this study, we would like to give w_j to each criterion equally. Thus, Eq. (2.12) is modified to $\Psi(y^0, y_i) = \sum_{j=1}^{n} \frac{w_j}{n}\, \alpha(y^0, y_i), \quad \forall i \in \{1,2, \dots, m\}$. Furthermore, the five decision-makers gave the score independently. So, the average score will be calculated as $G_{ij} = \frac{\sum_{k=1}^{K} g_{ij}^{k}}{K}$ where k is the expert k^{th}, $\forall k \in \{1,2, \dots, K\}$.

3.5 Data Analysis

The analysis follows the grey relational analysis procedure rigorously. However, please note that this is an example of steel material of a construction project.

CHAPTER 4

RESULT AND ANALYSIS

This chapter expresses the results from steps in the grey relational analysis which can be shown as four sections consecutively.

4.1 Decision-making Matrix Construction

The decision-making matrix is calculated using the modified equation, which be called a group decision-making matrix and can be shown using Eq. (2.7), as illustrated in Table 4.1.

$$G = \begin{bmatrix} G_{11} & G_{12} & \cdots & G_{1n} \\ G_{21} & G_{22} & \cdots & G_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ G_{m1} & G_{m2} & \cdots & G_{mn} \end{bmatrix}$$

Table 4.1 A group decision-making matrix.

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14
A1	3.60	2.20	2.80	2.40	3.20	2.80	3.20	2.60	2.80	3.00	2.40	2.60	2.20	2.60
A2	3.20	2.80	3.40	3.00	3.00	3.20	2.80	2.80	2.80	3.40	2.20	2.60	2.40	2.20
B1	2.40	2.40	3.00	2.60	3.00	2.80	2.40	2.60	2.20	2.60	2.60	2.80	2.60	2.40
B2	2.60	3.20	3.00	3.00	3.20	3.80	3.20	3.60	2.40	2.60	3.00	3.60	2.80	3.20
C	3.20	2.20	3.00	2.80	1.80	2.40	2.00	3.00	2.40	2.80	2.20	2.00	1.80	2.60

4.2 Performance Value Normalization

Alternatives' performance values are normalized and combined into a comparability sequence $Y_i = (y_{i1}, y_{i2}, y_{i3}, \dots, y_{in})$. The larger-the-better criteria and the smaller-the-better criteria are calculated using Eq. (2.8) and (2.9), respectively. The normalized performance value is calculated using Eq. (2.9), as shown in Table 4.2.

$$y_{ij} = \frac{Max\{G_{ij}, i = 1,2,\dots,m\} - G_{ij}}{Max\{G_{ij}, i = 1,2,\dots,m\} - Min\{G_{ij}, i = 1,2,\dots,m\}}$$

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

Table 4.2 The normalized performance value matrix.

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14
A1	1.00	0.00	0.00	0.00	1.00	0.29	1.00	0.00	1.00	0.50	0.25	0.38	0.40	0.40
A2	0.67	0.60	1.00	1.00	0.86	0.57	0.67	0.20	1.00	1.00	0.00	0.38	0.60	0.00
B1	0.00	0.20	0.33	0.33	0.86	0.29	0.33	0.00	0.00	0.00	0.50	0.50	0.80	0.20
B2	0.17	1.00	0.33	1.00	1.00	1.00	1.00	1.00	0.33	0.00	1.00	1.00	1.00	1.00
C	0.67	0.00	0.33	0.67	0.00	0.00	0.00	0.40	0.33	0.25	0.00	0.00	0.00	0.40

4.3 Reference Sequence Definition

By using Eq. (2.10),

$$y^0 = (y_1^0, y_2^0, \dots, y_n^0)$$

$$= \left(\max_{i=1\to m} y_{i1}, \max_{i=1\to m} y_{i2}, \max_{i=1\to m} y_{i3}, \dots, \max_{i=1\to m} y_{in}\right)$$

Thus, the reference sequence is $y^0 = (1.00, 1.00, 0.86, 0.67)$.

4.4 Grey Relational Coefficient Calculation

The grey relational coefficient (GRC) can be obtained by using Eq. (2.11). Please note that δ is a pre-determined parameter by the analyst which it equal to 0.5 for this study. Table 4.3 shows the GRC values.

$$\alpha\left(y^0, y_{ij}\right) = \frac{\Delta_{min} + \delta\Delta_{max}}{\Delta_{\mathrm{ij}} + \delta\Delta_{max}}, \quad \forall i \in \{1,2,..,m\}; j \in \{1,2,\dots,n\}$$

Table 4.3 The grey relational coefficient matrix.

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14
A1	1.00	0.33	0.33	0.33	1.00	0.41	1.00	0.33	1.00	0.50	0.40	0.44	0.45	0.45
A2	0.60	0.56	1.00	1.00	0.78	0.54	0.60	0.38	1.00	1.00	0.33	0.44	0.56	0.33
B1	0.37	0.43	0.49	0.49	1.00	0.47	0.49	0.37	0.37	0.37	0.58	0.58	0.90	0.43
B2	0.38	1.00	0.43	1.00	1.00	1.00	1.00	1.00	0.43	0.33	1.00	1.00	1.00	1.00
C	1.00	0.43	0.60	1.00	0.43	0.43	0.43	0.65	0.60	0.55	0.43	0.43	0.43	0.65

4.5 Grey Relational Degree Calculation

The grey relational degree (GRD) can be obtained by using Eq. (2.12). As mentioned before, w_i is equal for all $i \in \{1,2,\dots,n\}$. Table 4.4 shows the GRD values.

$$\Psi(y^0, y_i) = \sum_{j=1}^{n} w_j \alpha(y^0, y_i), \quad \forall i \in \{1,2,..,m\}$$

Table 4.4 The grey relational degrees.

	A1	A2	B1	B2	C
$\Psi(y^0, y_i)$	0.571330957	0.651648352	0.523840518	0.826105442*	0.574985884

Table 4.4 shows that regional supplier B2 is the best performance supplier in case of risk corresponding to three dimensions: time, cost, and quality risk factors. The problem is not a complex issue if no sub-risk factors carry out different opinions of decision-makers. The grey relational analysis technique assists the decision-makers in choosing the right supplier for steel material. In this analysis, regional supplier B2 is the highest-performance vendor with a GRD of 0.826105442, and the lowest-performance vendor is regional B1 with a GRD of 0.523840518.

By considering the normalized performance value matrix, regional supplier B1 works well on cost and quality risk factors by significantly dominating other competitors. Additionally, local supplier A2 can be the secondary supplier since it is the second-ranked supplier with high performance in some aspects, such as an efficient workforce, good work scheduling, and high experience in steel material.

CHAPTER 5

CONCLUSION

This chapter concludes the study according to the research objectives. Section 5.1 draws conclusions compatible with two objectives. Section 5.2 recommends the observations made during the study project and its results. Section 5.3 guides future research for interested researchers.

5.1 Conclusion

The grey relational analysis evaluated suppliers' performance based on supply chain risk factors. Five decision-makers independently scored each vendor corresponding to fourteen criteria. The GRA procedure can work on group decisions and eliminate score deviation by the sequence reference mechanism. The chosen vendor for this construction project was the regional supplier B2, with the highest grey relational degree of 0.826105442. Nonetheless, the second order supplier, local supplier A2, is an exciting choice. The supply chain management may choose it as the secondary supplier since it is the local vendor and works well on some risk factors.

The study found that the grey relational analysis, a simple and straightforward technique, was easily applicable to supply chain risk analysis in the construction industry. Its calculation steps were straightforward, logical, and traceable. The case study also demonstrated that the supplier selection based on supply chain risk, specifically on the steel supplier of the sample construction project, was reasonable and uncontested. This underscores the potential of the grey relational analysis for future applications in the industry.

5.2 Recommendations

The drawbacks of the grey relational analysis technique are two pre-determined parameters, δ and w_j, which an analyst must consider before proceeding with the analysis. The δ appears in Eq. (2.11) while w_j appears in Eq. (2.12). Technically, $\delta \in [0,1]$. The analyst gives more importance to the best practice when $\delta \to 1$; on the other hand, the analyst gives less importance to the best practice when $\delta \to 0$. Merely, it is a subjective parameter. The analyst must carefully select this value. The w_j is the weight of criterion j. The higher w_j means a more important criterion than the other. We recommend other multi-criteria decision-making tools, such as the analytic hierarchy process (AHP), to calculate the weighted criteria before proceeding with the grey relational analysis technique.

5.3 Futrue Research

As highlighted in the previous section, the grey relational analysis has certain drawbacks, particularly the analyst’s pre-determined parameters, δ and w_j. This opens up an exciting avenue for future research. Interested researchers might explore how to determine δ and w_j in a reasonable and traceable manner. There are numerous techniques that could be employed, from the analytic hierarchy process to more advanced methods such as particle swarm optimization, artificial neural networks, or other machine learning tools.

REFERENCES

Abdullah, W. Z. W., and Nasir, S. R. M. (2017). "Supply chain integration issues and challenges in industrialised building system (IBS) construction projects in Malaysia." **Malaysian Construction Research Journal**, 22, 2: 73-83.

Algahtany, M., Alhammadi, Y., and Kashiwagi, D. (2016). "Introducing a new risk management model to the Saudi Arabian construction industry." **Procedia Engineering**, 145: 940-947.

Bakhtavar, E., Valipour, M., Yousefi, S., Sadiq, R., and Hewage, K. (2021). "Fuzzy cognitive maps in systems risk analysis: a comprehensive review." **Complex & Intelligent Systems**, 7: 621-637.

Bao, Z., Lee, W. M., and Lu, W. (2020). "Implementing on-site construction waste recycling in Hong Kong: Barriers and facilitators." **Science of the Total Environment**, 747: 141091.

Charmaz, K. (2000). Constructivist and objectivist grounded theory. In V NK Denzin in Y. Lincoln (Ed.), **Handbook of Qualitative Research** (pp. str. 509-535).

Chen, Z., Hammad, A. W., and Alyami, M. (2024). "Building construction supply chain resilience under supply and demand uncertainties." **Automation in Construction**, 158: 105190.

Coleman, L. (2006). "Frequency of man-made disasters in the 20th century." **Journal of Contingencies and Crisis Management**, 14, 1: 3-11.

Cooper, M. C., Lambert, D. M., and Pagh, J. D. (1997). "Supply chain management: more than a new name for logistics." **The international journal of logistics management**, 8, 1: 1-14.

Ekanayake, E. M. A. C., Shen, G. Q., Kumaraswamy, M. M., and Owusu, E. K. (2022). " Identifying supply chain vulnerabilities in industrialized construction: an overview." **International journal of construction management**, 22, 8: 1464-1477.

El-Sayegh, S. M. (2008). "Risk assessment and allocation in the UAE construction industry." **International journal of project management**, 26, 4: 431-438.

Ertuğrul, İ., Öztaş, T., Özçil, A., and Öztaş, G. Z. (2016). "Grey relational analysis approach in academic performance comparison of university a case study of Turkish universities."

Finch, P. (2004). "Supply chain risk management." **Supply chain management: an International Journal**, 9, 2: 183-196.

Glaser, B., and Strauss, A. (2017). **Discovery of grounded theory: Strategies for qualitative research**. Routledge.

Hatmoki, J. U. D., and Scott, S. (2010). "Stimulating the impact of supply chain management practice on the performance of medium-sized building projects." **Construction Management and Economics**, 28, 1: 35-39.

Ho, W., Zheng, T., Yildiz, H., and Talluri, S. (2015). "Supply chain risk management: a literature review." **International journal of production research**, 53, 16: 5031-5069.

IBM. (n.d.). **What is SCRM?** accessed May 20, 2024. available from https://www.ibm.com/topics/supply-chain-risk-management

Karamoozian, A., and Wu, D. (2024). "A hybrid approach for the supply chain risk assessment of the construction industry during the COVID-19 pandemic." **IEEE Transactions on Engineering Management**.

Kersten, W., Hohrath, P., Boeger, M., and Singer, C. (2011). "A supply chain risk management process." **International Journal of Logistics Systems and Management**, 8, 2: 152-166.

Kitchin, R., and Freundschuh, S. (2018). Cognitive mapping. In **Cognitive mapping** (pp. 1-8): Routledge.

Kosko, B. (1992). **Neural networks and fuzzy systems: a dynamical systems approach to machine intelligence**. Prentice-Hall, Inc.

Larson, P. D. (2001). "Designing and managing the supply chain: Concepts, strategies, and case studies." **Journal of Business Logistics**, 22, 1: 259.

Liu, S., Yang, Y., and Forrest, J. (2017). Grey data analysis. In (Vol. 10(1007), pp. 978-981). Springer Singapore, Singapore.

Lutkevich, B. (n.d.). **Supply Chain**. accessed May 20, 204. available from https://www.techtarget.com/whatis/definition/supply-chain#:~:text=A%20supply%20chain%20is%20the,delivery%20to%20the%20end%20user

Manuj, I., and Pohlen, T. L. (2012). "A reviewer's guide to the grounded theory methodology in logistics and supply chain management research." **International Journal of Physical Distribution & Logistics Management**, 42, 8/9: 784-803.

Micheli, G. J., Cagno, E., and Zorzini, M. (2008). "Supply risk management vs supplier selection to manage the supply risk in the EPC supply chain." **Management Research News**, 31, 11: 846-866.

Mills, A. (2001). "A systematic approach to risk management for construction." **Structural survey**, 19, 5: 245-252.

Neiger, D., Rotaru, K., and Churilov, L. (2009). "Supply chain risk identification with value-focused process engineering." **Journal of operations management**, 27, 2: 154-168.

Noble, H., and Mitchell, G. (2016). "What is grounded theory?" **Evidence-based nursing**, 19, 2: 34-35.

Norrman, A., and Jansson, U. (2004). "Ericsson's proactive supply chain risk management approach after a serious sub-supplier accident." **International Journal of Physical Distribution & Logistics Management**, 34, 5: 434-456.

Norrman, A., and Lindroth, R. (2004). "Categorization of supply chain risk and risk management." **Supply chain risk**, 15, 2: 14-27.

Papageorgiou, E. I., and Salmeron, J. L. (2012). "A review of fuzzy cognitive maps research during the last decade." **IEEE transactions on fuzzy systems**, 21, 1: 66-79.

Poczeta, K., Papageorgiou, E. I., and Gerogiannis, V. C. (2020). "Fuzzy cognitive maps optimization for decision making and prediction." **Mathematics**, 8, 11: 2059.

Puljić, M. (2010). "The influence of cognitive biases on managerial perceptions of supply chain risk." **The International Supply Chain Risk Management Network (ISCRiM)**, 24.

Qazi, A., Quigley, J., and Dickson, A. (2015). Supply Chain Risk Management: Systematic literature review and a conceptual framework for capturing interdependencies between risks. In 2015 **International Conference on Industrial Engineering and Operations Management (IEOM)** (pp. 1-13): IEEE.

Rajesh, R., and Ravi, V. (2015). "Supplier selection in resilient supply chains: a grey relational analysis approach." **Journal of cleaner production**, 86: 343-359.

Rudolf, C. A., and Spinler, S. (2018). "Key risks in the supply chain of large scale engineering and construction projects." **Supply chain management: an International Journal**, 23, 4: 336-350.

Salmeron, J. L., and Papageorgiou, E. I. (2012). "A fuzzy grey cognitive maps-based decision support system for radiotherapy treatment planning." **Knowledge-Based Systems**, 30: 151-160.

Schuerkamp, R., and Giabbanelli, P. J. (2023). "Extensions of fuzzy cognitive maps: a systematic review." **ACM Computing Surveys**, 56, 2: 1-36.

Segerstedt, A., and Olofsson, T. (2010). "Supply chains in the construction industry." **Supply chain management: an International Journal**, 15, 5: 347-353.

Shishehgarkhaneh, M. B., Moehler, R. C., Fang, Y., Aboutorab, H., and Hijazi, A. A. (2024). "Construction supply chain risk management." **Automation in Construction**, 162: 105396.

Shojaei, P., and Haeri, S. A. S. (2019). "Development of supply chain risk management approaches for construction projects: A grounded theory approach." **Computers & Industrial Engineering**, 128: 837-850.

Shokouhyar, S., Pahlevani, N., and Mir Mohammad Sadeghi, F. (2019). "Scenario analysis of smart, sustainable supply chain on the basis of a fuzzy cognitive map." **Management research review**, 43, 4: 463-496.

Sugathadasa, P. T. R. S., Herath, R. P. H. M. A., and Thibbotuwawa, A. (2021). "Supply chain risk assessment and mitigation approaches for small-sized road construction projects." **Engineer: Journal of the Institution of Engineers, Sri Lanka,**, 54, 3: 39-48.

Tang, C. S. (2006). "Perspectives in supply chain risk management." **International journal of production economics**, 103, 2: 451-488.

Tummala, R., and Schoenherr, T. (2011). "Assessing and managing risks using the supply chain risk management process (SCRMP)." **Supply chain management: an International Journal**, 16, 6: 474-483.

Turner, C., and Astin, F. (2021). "Grounded theory: what makes a grounded theory study?" **European Journal of Cardiovascular Nursing**, 20, 3: 285-289.

Young, D. A., Haas, C. T., Goodrum, P., and Caldas, C. (2011). "Improving construction supply network visibility by using automated materials locating and tracking technology." **Journal of Construction Engineering and Management**, 137, 11: 976-984.

Zheng, P. (2024). "Supply chain operation evaluation and management decision by fuzzy cognitive map model." **Expert Systems**, 41, 5: e13022.

Zou, Y., Kiviniemi, A., and Jones, S. W. (2017). "Retrieving similar cases for construction project risk management using Natural Language Processing techniques." **Automation in Construction**, 80: 66-76.

APPENDIX

APPENDIX A

Questionnaire

Questionnaire

This form is the questionnaire for a research project of Mr. Mao JIA, a student in the Master Degree of Engineering Program in Engineering Management at Silpakorn University. The topic is “Construction Supply Chain Risk Management: A Case Study”

There is one part. It asks asks the opinion about the suppliers’ performance according to the performance in supply chain management. Forteen risk factors are divided into three main risk factors. The details and their statements are shown the table below.

Main risk factors	Code	Sub-risk factors
Critical time risk factors	R1	Material delays due to no appropriate communication
	R2	Delay due to material condition and wastages such as weather impacts.
	R3	Machines and equipment are not ready to be used due to lack of maintenance.
	R4	Project delays due to environment effects.
	R5	Deficit of workforce due to workforce market and labor’s absenteeism
Critical cost risk factors	R6	Loss due to material condition and wastages such as weather impacts.
	R7	Project delays due to environmental impacts.
	R8	Overtime cost due to workforce deficit.
	R9	Improper planning and scheduling due to defective estimation.

Main risk factors	Code	Sub-risk factors
Critical quality risk factors	R10	Incorrect selection of supplier because not knowing the right type of supplier to order.
	R11	Material defects due to weather impacts.
	R12	Project delays due to environmental impact to material quality.
	R13	Project failures due to poor engineering techniques.
	R14	Material delays due to no appropriate communication

It is a five-point Likert scale as shown in the table below.

	R1	R2	R3	R4		R5	R6	R7	R8	R9	R10	R11	R12	R13	R14
A1															
A2															
B1															
B2															
C															

Thank you very much for your cooperation. The data are kept secret and unopened to a third-party organization. The purpose of this study is academic only.

VITA

NAME Mr. Jia MAO