Title	マルチモーダルロジスティクスおよび輸送システムにおけるルート選択のための多基準意思決定に関する研究
Author(s)	KAEWFAK, Kwanjira
Citation	
Issue Date	2021-09
Type	Thesis or Dissertation
Text version	ETD
URL	http://hdl.handle.net/10119/17520
Rights	
Description	Supervisor:Huynh Nam Van, 先端科学技術研究科, 博士

A Study on Multi-Criteria Decision Making for Route Selection in Multimodal Logistics and Transportation Systems

KAEWFAK KWANJIRA

Japan Advanced Institute of Science and Technology

Doctoral Dissertation

A Study on Multi-Criteria Decision Making for Route Selection in Multimodal Logistics and Transportation Systems

KAEWFAK KWANJIRA

Supervisor: Professor HUYNH VAN NAM

Graduate School of Advanced Science and Technology
Japan Advanced Institute of Science and Technology

Knowledge Science

September, 2021

Abstract

Freight transportation is considered as a crucial part of the logistics and supply chain systems that ensures efficient operation and time of raw product and finished goods. As a result of the globalization of trade, the traditional mode of transportation such as truck transportation is no longer a workable solution. Traffic congestion and environmental problems associated with truck transportation are the main concerns. Accordingly, the European transport policy seeks to reduce pollution from road transportation and search for better modes of transportation which are more energy-efficient. Multimodal transportation is currently considered as one of the most important elements of modern transportation systems. Crucially, there are several issues needed to be identified when discussing about the multimodal freight transportation systems. However, the analyzes can be complex due to the fact that there are many factors associated with the multimodal transportation and many interactions between different modes.

The route selection strategy has become the primary focus of the design of the network of the multimodal transportation. The cost and time of transportation and also the associated risks should be considered when choosing the transportation route. However, it is considered as complex multiple objective problems that are characterized by several conflicting criteria, inaccurate and ambiguous parameters and the vagueness of the human thinking.

To overcome these problems, this research develops a five-step decision support framework by utilizing the Multi-Criteria Decision Making (MCDM) tool. The first step helps define the scope of this research by collecting the data of all the routes under consideration. In the second step, the cost and time of transportation of each route are identified according to the actual test data. The third step focuses on the evaluation of the multimodal transportation risks by utilizing the integrated quantitative risk analysis, Fuzzy Analytic Hierarchy Process (FAHP) and Data Envelopment Analysis (DEA) methodology. In the fourth step, the weights of each factor are determined relied on the opinions of the 5 decision makers, who either work in the field of transportation or work as an academic researcher, with a neutral understanding of the risks associated with transportation and with a direct involvement within the transportation process and logistics management for more than 20 years. The significance weight of criteria which attained from Fuzzy Analytic Hierarchy Process (FAHP) can be integrated into a multi-objective optimization. Lastly, the Zero-one Goal Programming (ZOGP) is utilized to define the optimal multimodal transportation route. This research uses this approach to study the existing routes of coal transportation in Thailand. To validate the model as well as results of this research, a sensitivity analysis is used on each of the Multi-Criteria Decision Making (MCDM) methods under consideration, ensuring accuracy and practicality of the decision support tool.

This research contributes to the improvement of the decision support approach which can be more flexible and can be applied to select the optimal route that can optimize cost, time, and risks of the multimodal transportation effectively. This method can offer guidance to efficiently determine the best route which would improve the logistic system performance. The findings show that the approach can inform the decision makers about the optimal route according to the attributes mentioned above.

Keywords:Multimodal transportation, Route selection, Multi-Criteria Decision Making (MCDM), Risk analysis, Optimization problem.

Acknowledgement

This study would not have been a success without the financial support from JAIST-SIIT-NECTEC Dual Doctoral Degree Program Scholarship, Japan Advanced Institute of Science and Technology (JAIST), Sirindhorn International Institute of Technology (SIIT), Thammasat University and National Electronics and Computer Technology Center (NECTEC).

First of all, I would like to express my sincere gratitude to my supervisors Prof. Dr. Huynh Van Nam and Assoc. Prof. Dr. Veeris Ammarapala for supporting of my doctoral study and research as well as for providing me motivation and valuable knowledge and guidance. I am grateful for having such great supervisors and mentors for my doctoral study.

Along with my supervisors, I would like to thank the thesis committees: Prof. Dr. Kohda Youji, Prof. Dr. Yuizono Takaya, Assoc. Prof. Dr. Kim Eunyoung and Assoc. Prof. Dr. Ryoke Mina for their encouragement and thoughtful feedback.

Last but not the least, no one has been more important to me in supporting my research than my family members. I would like to express my gratitude to my parents for their love, care, and sacrifice which have helped prepare me for my future. I am also deeply grateful that I have my boyfriend who has offered his love, understanding, and support which have helped me complete this study. Also, I would like to thank my sister for her valuable support and encouragement.

Lastly, I would like to thank everyone who has directly or indirectly supported me through the entire process of this research.

Kwanjira Kaewfak
September, 2021

Contents

This dissertation was prepared according to the curriculum for the Collaborative Education Program organized by Japan Advanced Institute of Science and Technology and Sirindhorn International Institute of Technology, Thammasat University.

List of Figures

List of Tables

List of Abbreviations

Abbreviations	**Terms**
MCDA	Multiple Criteria Decision Analysis
MCDM	Multiple Criteria Decision Making
MADM	Multiple Attribute Decision Making
MODM	Multiple Objective Decision Making
AHP	Analytic Hierarchy Process
FAHP	Fuzzy Analytic Hierarchy Process
DEA	Data Envelopment Analysis
ZOGP	Zero-one Goal Programming
MZOGP	Multilayer Zero One Goal Programming
SAW	Simple Additive Weighting
DSF	Decision Support Framework
QRA	Quantitative Risk Assessment
ELECTRE	Elimination and Choice Translating Reality
TOPSIS	Technique for Order Preference by Similarity to the Ideal Solution
MAUT	The Multi-Attribute Utility Theory
PROMETHEE	Preference Ranking Organization Method for Enrichment Evaluation
VIKOR	Vlse Kriterijumska Optimizacija Kompromisno Resenje or Multiple Criteria Optimization and Compromise
TFN	Triangular Fuzzy Number
LLSM	Logarithmicleast squares method
DMU	Decision Making Unit
CR	Consistency Ratio
CI	Consistency Index
RI	Random Index
UNCTAD	United Nations Conference on Trade and Development
EU	The European Union
LSPs	Logistics Service Providers
EGAT	Electricity Generating Authority of Thailand
KMO	Kaiser-Meyer-Olkin measure
FFUCOM	Fuzzy Full Consistency Method
FMWM	Fuzzy Best-Worst Method

Chapter 1

Introduction

The transportation of goods is a major component of the supply chain and logistics. It must be concerned in order to allow for the efficient transportation and rapid accessibility to raw materials and finished goods [1]. As global supply chain requirements evolve, multimodal transportation is now the most crucial element for modern logistics and transportation systems, particularly for long-haul and big volume transportation. The Multimodal Transport Handbook written by UNCTAD defines Multimodal transportation as the transportation of goods through multiple modes of transportation from a place of origin, then passing interface point(s) before arriving at a destination point where a carrier arranges the whole transport. Multimodal transportation can be perceived as a crucial step forward to make local industry and international commerce more competitive and efficient. This is due to its ability to create a fluid movement of merchandise and more effective control on the transport line. The key benefit of multimodal transportation is that it can reduce transportation costs and delays as well as fuel costs. In addition to saving up for the market, it also brings environmental sustainability.

The strategy on multimodal transportation in terms of the selection of route is a crucial element of transport logistics. It solves the problem related to the freight route choice while also considering many other limitations which include the costs on transport logistics, time used, and other risks. It is the most efficient approach to generate an optimized route selection. Most previous research on multimodal transportation route choice have concentrated only on how to reduce cost and time [2, 3, 4, 5] while several other studies focus on minimum risk [6, 7, 8].

Risk is a major consideration when selecting a transportation route. Risk may be related to accidents that lead to higher costs, delays, and substandard logistical systems [8, 9]. Furthermore, regarding the process of transportation and logistics, the UNCTAD Secretariat (2003) claimed that risks involve not only direct costs, but also the reduction in export competitiveness. As such, in choosing transportation routes, it is crucial that all three aims, namely cost, time, and risk, are taken into account within the optimization model.

Nevertheless, taking all these aspects into account makes complex route selection problematic. To tackle this, numerous researchers have developed mathematical models in order to enhance route selection process for the improvement of the logistics and transportation performance. Yang et al. [10] set out a multi-purpose optimization model related to the rail route selection in China, while Zhang et al. [11] created a decision support tool for the selection of rail route for dangerous liquid. While many researches have been studied on this topic, they have focused on the optimum choice of routes for multimodal transport [8, 9, 12]. For instance, Meethom and Koohathongsumrit [12] provided an optimization model for goods transported in containers using dynamic programming. The aim of these studies was to search for the best route taking into account all the factors together with specific optimization algorithms. Nevertheless, these studies focus mainly on the well-known transportation system and were predominantly influenced by field experts in the process of evaluating the significance of weights. Consequently, the direct application of the above methods is not able to effectively tackle the problem of the multimodal route selection.

To address this gap, this research has proposed a multi-purpose optimization model that considers transportation cost, time, and risks. The Fuzzy Analytic Hierarchy Process (FAHP) and Zero-one Goal Programming (ZOGP) are chosen for solving the problem of how to choose the best route for the multimodal transportation. The feasibility of the proposed methodology is illustrated through an actual case study. This research goals to contribute to the improvement of a methodology that would make it possible to carry out a pragmatic plan of route selection. This flexible method can be adopted in the industrial sector with all practices of multimodal transportation.

The idea behind this study is to determine the best route which would reduce costs, time, and risks within the systems of multimodal transportation. This can be done in five steps. First, the study areas and all the related routes are defined. Second, the transport cost as well as time of each route are calculated. Then, qualitative risk analysis is integrated and evaluated by the experts. Next, criteria are prioritized with the use of FAHP. The last step involves the optimization of the route. The results demonstrated that this approach is capable of providing guidance for selecting optimum cost, time, and risk for multimodal transportation within the coal industry in an efficient manner.

1.1 Problem statement

In the recent years, several industries have been working on how to reduce the logistical and transport costs in order to stay competitive. At the moment, road transport remains the major element of the logistics and transportation system. The EU Transport Commission claimed that freight transportation, particularly road freight transportation is increasing, with the latter projected to rise by approximately around 40% in 2030, and by around 80% in 20 years after. In this way, they try to decrease truck transport and make it less polluting and more efficient in terms of energy. The field of multimodal transport has been an area under focus due to the issues of road safety, congested traffic, and other environmental concerns. As a result, there has been a growing interest in the topic of multimodal freight transportation, which has been considered as one of the best solutions that can help decrease costs within the logistics system. Being able to choose the most optimal route, many businesses can reduce costs and time used in the transportation process and, in turn, boost their competitive advantage. Nevertheless, this issue is complex considering the complication in the selection of routes, multiple criteria that can conflict with each other, as well as the inaccuracy of parameters. Furthermore, the vagueness and uncertainty of experts' subjective views further make the issue more problematic.

1.2 Research objectives

This study offers a framework for selecting the best routes of multimodal transportation within coal industry with the aim of prioritizing them for practical comprehension and implementation within the business sector. The main objective of this research is to classify different factors related to multimodal transportation. To evaluate the most significant factors for the implementation of multimodal transportation practices, this study looks into coal manufacturing firms in Thailand. The second goal is making a contribution to the study of the risk analysis process by determining the significant risk scores and able to effectively manage the multimodal transportation. The final goal is to optimize multimodal transport routes, and, thereby, helps companies reduce their costs, time and risks incurred within the multimodal transportation systems.

1.3 Scope of study

This study is restricted to planning in multimodal coal transportation concerning road, rail (potential), and maritime transportation. Nevertheless, it has no interest in air transportation due to its greater cost and energy consumption. The case study in this research focuses on the Thai coal industry, which has been moved to be part of the Cement industry. This study concerns the multimodal transportation routes between Sri-Chang, Chonburi Province and Sara Buri Province, focusing on the Central Region of Thailand.

1.4 Contribution of research

The study should make a great contribution to the overall knowledge in the area. The key fields of contribution are as follows:

- The study suggests a practical risk analysis framework for reducing risk assessment bias. It also contributes to a decision support system to assess quantitative transportation risk. The research provides valuable information for experts and researchers to analyze and prioritize transportation risks and to optimize routes taking into account the costs, time and risks incurred.
- The conceptual design proposed within the theoretical model can be validated and well-explained, leading to it being in good fit with the data. As a result, this research greatly contributes to the field by introducing a set of possible factors that have an impact on the five types of common risks which are environmental, security, freight-damage, infrastructure, and operational risk. Multimodal transportation risks can be classified into two parts using qualitative as well as quantitative approaches. This complex way of classification not only facilitates the identification of risk factors, but also works as a beginning point for researchers to design an effective transportation risk index model which can be applied on multimodal transportation systems.
- While some existing measures have been adapted, new measures are also developed in this research. It also follows adequate methodological process in order to effectively measure the robustness and reliability of the model. Therefore, this research shows a contribution of quantitative methodology to the research in the field of international logistics and transportation.

1.5 Significance of research

The aim of this research is to determine and identify the best multimodal routes. This research empirically looks at multimodal coal transportation as to develop the Decision Support Framework (DSF) in combination with several other valid models. Moreover, the risk assessment model can greatly help facilitate the improvement of multimodal transportation system by providing visible, predictable, and measurable freight transport operations. Several integrated techniques are shown in order to achieve the optimal route regarding coal transportation, taking into consideration the cost, time, and risk criteria. This research aims to select the best transport routes for businesses while minimizing the complicating factors involved as to strategically improve robustness and effectiveness. The research is relevant for it utilizes modern techniques in the supply of services related to logistics and transportation.

1.6 Limitations of research

There are some limitations with regard to the data in this study which are mostly collected in specific setting. Therefore, some pieces of information have to be adjusted before they can be applied on other cases. For instance, experts' preference scores have to be constructed with great care. In general, the data and their analyses vary according to the contexts of different industries. Also, another limitation concerns the issue of the calculation of costs because the transportation on the analyzed routes is usually multimodal. The research should, therefore, consider the potential moderating effects resulting from dependency as well as collaborative or conflictual relationships between modes of transportation and distribution channels, for instance, shipping cost, delivery cost and insurance cost.

1.7 Steps of research process

To effectively investigate the issue under research, the researcher utilizes both quantitative and qualitative approaches. The first chapter of this thesis looks at the research background, objectives, framework, methodologies, and potential contributions. In addition, a brief research outline is also provided. The steps of research process are as follows:

- Study areas and all the routes are identified, with the database collected from experts with impartial understandings of multimodal transportation. These experts include researchers, logistics managers, and shipping managers.

- The actual freight routes in multimodal transportation from SriChang island in Chonburi to Saraburi are investigated. The transportation modes that are studied are road, ship, and railway.

- Related research on multimodal transportation and those concerning quantitative and qualitative decision making are studied. The cost, time, and risk factors are assessed in each route.

- The significance of different criteria in each situation is determined using the Fuzzy Analytics Hierarchy Process (FAHP). The Quantitative Risk Assessment (QRA) in multimodal transportation from the experts' viewpoints are combined as part of the research model in this thesis.

- Multimodal transportation routes are optimized by utilizing mathematical programming method. The data on the significant weights from FAHP together with the other information from entrepreneurs are utilized as to identify functionalities and constraints.

- Analysis and conclusion are provided.

1.8 Structure of report

Essentially, this research follows the structure of a PhD thesis. It identifies problems and follows the proposed conceptual framework which is supported by theories that can test its validation empirically and conceptually. The general overview and structure of this thesis are addressed in this section. The research can be divided into 5 parts as follows:

- Chapter 1: Introduction. This chapter introduces the background of the thesis, providing problem statement, research objectives, potential contributions, research framework, and research processes.

- Chapter 2: Literature review. This chapter discusses previous studies in the field of multimodal transportation and its relation to multimodal transportation risk management and analysis. It also addresses the popular techniques related to multi-criteria decision-making.

- Chapter 3: Research Methodology. This chapter demonstrates and applies research methodology on the various aspects under research.

– Chapter 4: Case study and analysis. This chapter presents findings and results from the previous chapters and demonstrates them together with the practical case study.

– Chapter 5: Conclusion, Limitation, and Further Study. This chapter gives a concise conclusion of the research while at the same time identifying limitations and providing the further study.

Chapter 2

Literature Review

This part focuses on the previous studies from multiple reliable sources. Literature review is conducted in groups in order to thoroughly summarize each topic including multimodal transportation and the selection of routes, risk analysis in transportation, Multi-Criteria Decision Making (MCDM), Fuzzy Analytical Hierarchy (FAHP), Data Envelopment Analysis (DEA), and Zero-one Goal Programming (ZOGP).

2.1 Multimodal transportation and route selection

The transferring of products is a major element of the systems of logistics and supply chain. The growing demand for goods transportation means that the development of strategies related to it is urgently needed in order to achieve sustainability [1]. According to the 2017 statistics on the trade globalization conference, the percentage of the EU's inland freight transported by cars on roads constituted 76.7%, which was four times higher than that done by trains (17.3%), while the remaining 6.0% was transported by inland waterways. At the same time, the external costs incurred on the society is quite high. Every kind of externality created by freight transportation needs great attention. The fast-growing market of goods transportation will negatively impact the environment, leading to worsening climate change, noise and air pollution, and traffic problems [13]. Moreover, with more vehicles on roads, the risk of accidents also increases [14]. This makes it necessary to make a shift from relying on transporting goods by cars to the system of multimodal freight transportation. Concerning the EU, the policies related to the system of multimodal transportation have been a great success.

Within the industry of goods transportation, multimodal freight transportation is a crucial aspect [15, 16]. The multimodal freight transportation is defined as the movement of products in a vehicle or a loading unit with the use of two or more transportation modes (road, train, sea, and air). This is in order accentuate the strengths of various modes of transportation within one integrated chain of transportation, resulting in the improvement of economic performance which can be achieved as the best mode of transportation is selected for each part of a trip [17, 18].

The primary benefit of multimodal transportation is the low amount external cost, constituting only around one-thirds of the external cost incurred when using only a general freight truck [19]. Nonetheless, the external cost difference may be larger due to traffic congestion. Multimodal freight transportation consumes less energy, meaning it is in accordance with the EU's sustainable goals. As a result, it has been promoted by policymakers at every level [20].

The selection of route can help reduce the friction of distance between different locations, lowering the time and costs of all transport users which include individuals who want to improve their mobility and those big corporations that have to manage complicated supply chains. In the conditions like these, many methods have been created in order to tackle problems related to the issue of how to select the best routes [2, 3, 4, 21]. Concerning multimodal transportation, Chang and Cheng [22] examined network planning and path optimization, while Southworth and Peterson [3] applied commodity flow survey to study the system of multimodal transportation in the United States. Route selection, which can help reduce costs, time, and risks, has three main dimensions as follows:

- Cost minimization: Selecting the right route can reduce the overall costs of transportation concerning the operating costs. The most direct route does not necessarily mean that it is the cheapest route, though it gets selected most of the time. When selecting a route, one must make sure that it is the least harmful to the environment, taking into account environmental effects.

- Time minimization: the problem of how to minimize time in transportation is one in which each shipping route is associated with the time incurred. The aim is to minimize the maximum time used in transporting all goods to the destination.

- Risk minimization: risk is a crucial factor when making a decision related to multimodal transportation. Within the logistical and transportation process, risk means accidents that lead to higher direct costs and lower competitive advantage, taking into account environmental aspects. All logistics service providers (LSPs) always need to include this aspect when making any decisions.

2.2 Transportation risk management

There are two different meanings for 'risk'. It can mean either a hazard or an exposure to misfortune, or, in another context, the likelihood that one might suffer from negative consequences. Over the past decade, risk management has been popularly applied on a broad range of activities both by governmental agencies and through industry's principal business practices [9, 23]. It has been established that 'risk' has been proven as having a significant impact on logistics and transportation. Events in the past have provided some good points regarding the importance of risk factors within transportation systems. Taking the example of the collisions of ships in the Strait of Malacca [24], for instance. The safety of marine traffic is badly affected by the danger caused by the difficulty to navigate in this high-risk area, which has the longest strait in the world (1,120 km). Another serious incident, the Viareggio accident [25] occurred in Italy in 2009. Fire damaged several houses and cars near the railway, with 32 people killed in the incident. Accordingly, to prevent similar losses in the future, risk management and risk analysis must be taken into account when managing any transportation activities.

Conceptually, risk is the possibility that the outcome does not align with the objectives of the system because of environmental differences. According to the literature review, risk is associated with both the uncertainty as well as its results [8, 9]. In this context, risk management can mean both the recognition of potential sources of risk as well as the implementation of adequate strategies with coordinated approach in order to make transportation less vulnerable to any types of risk [26]. In the same manner, Soeanu et al. [23] claimed that risk management introduces the notion that the probability of an occurrence can be reduced, and its impacts minimized.

Many previous studies [26, 27] have tackled the issue of risk management. Most of them particularly look at the topic of risk management. Overall, risk management has been examined both from qualitative perspective and quantitative perspective, with the first approach being dominant with great amount of reliable data and expertise available. The risk management process involves identifying and evaluating risk, with the first one being considered as a crucial phase with risk and its source being identified. Wu and Blackhurst [28] claimed that the important phase within the risk assessment process is when the categories of risk are identified before weighing, comparing, and quantifying different categories of risk.

2.3 Risk analysis

In multimodal freight transportation, risk is particularly associated with accidents which have critical impacts on the external costs of transportation, the delivery time, and the quality of the logistical system. Banomyong and Beresford [29] stated that the risk associated with transportation is of significance when making decisions. As a high level of uncertainty is accompanied by high cost, the uncertainty must be taken into account. Risk refers to both uncertainty and its outcomes. The analysis of risk has two steps: risk identification and risk assessment.

Risk assessment is a systematic procedure to systematically assess the effects or consequences of human actions. It is considered a vital tool for a safety policy. The variety within risk assessment is reflected in the way that there are different techniques no matter what the situation. Risk assessment has been discussed in previous studies as having three interconnected components which include risk identification, risk estimation, and risk evaluation [30].

2.3.1 Risk identification

Risk identification basically means the acknowledgement of the existence of the danger and then attempt to define its features. Most of the time, risks can be recognized and measured long before their negative impacts can be recognized. In other instances, risk identification is a way to review and predict potential hazards [9, 30].

2.3.2 Risk estimation

Risk estimation is when we scientifically determine the features of risks using quantitative approach, taking into consideration the magnitude, scale, and duration of time of potential negative consequences. The causes and effects are identified. Both risk estimation and risk identification nay include the process of modelling, monitoring, and analyzing. Their main purpose is to help us understand risks within the system of transportation and to know the nature of complex processes by which risks arise [26, 30].

2.3.3 Risk evaluation

Risk evaluation is when we make judgements about the significance of the probability of risks and their outcomes. This process is essential when determining a policy. With the purpose to compare different types of risks together, looking at them side by side with the benefits. It also looks for ways in which we can judge the social acceptability of risks, taking into account both political and managerial decisions because it is associated with the question of who is likely to gain and who is likely to lose, and how much should be compensated [26].

After we identify the risk, it is then estimated and evaluated. Them, there is an intervention (or non-intervention or a delay of an action) which has different natures depending on the risks as well as the policy-making style and framework. However, before it can be implemented, much of the risk assessment has already occurred, greatly affecting the following course of events.

2.4 Multi-Criteria Decision Making (MCDM)

Given the ever-increasing proliferation of decision-making methods, their comparative value must also be understood. All methods demonstrate numeric techniques to assist decision makers when they have to make decisions. This is done based on the effect of the alternatives on specific criteria and, as a result, on the general utility of the decision maker(s). Comparing decision methods in order to select the best one is difficult since there is a paradox, which can be solved when taking into consideration multiple actors, criteria, and aims. Multi-criteria decision making (MCDM) has been shown as the key for solving complex problems. It basically consists of five elements: aim, decision maker's preferences, alternatives, criteria, and results. Given the number of alternatives that are considered, differences between multi-attribute decision making (MADM) and multi-objective decision making (MODM) can be bridged; otherwise, the two have some characteristics in common. The latter is appropriate for the assessment of continuous alternatives where there are some constraints that have been predefined as decision variable vectors.

Objective functions are improved taking into account the constraints, whilst, at the same time, reducing the quality of the performance of the objective(s). In multi-attribute decision making (MADM), it covers the inherent characteristics which results in fewer number of alternatives being considered. The ultimate outcome is determined by the comparison of many different alternatives for each attribute under consideration [31, 32]. Various multi-criteria techniques have been applied in various research, for examples, transportation, logistics and supply chain management. MCDM models are perceived as a technique with broader classification that depends on designer's point of view, with the approach being either direct or indirect. The direct approach means that priorities are being assessed according to the inputs from the surveys which concern the beneficiary, society, or acquaintance, while with the indirect approach, criterion are separated in their components, assigned weights, and decision maker's judgement according to their experience.

MCDM is complicated because of the existence of several factors which are technical factor, institutional factor, economic factor, societal factor, and stakeholders. As a result, it concerns analyses related to engineering and management. Also, this procedure is quite controversial since objectives can result in varied solutions depending on the priority established those who make decisions. Additionally, a particular issue can be addressed using other methods depending on the functions. Each method or model has its own disadvantages and limitations [33]. For examples, ELECTRE, TOPSIS, MAUT, PROMETHEE, VIKOR etc.

2.4.1 Analytic Hierarchy Process (AHP)

MCDM methods are ways to approach information and make decision related to formal problems that have several conflicting objectives [34]. Many studies have utilized MCDM methods together with the Analytic Hierarchy Process (AHP) method to resolve real-world issues. Around half a century ago, Thomas L. Saaty introduced AHP technique which approaches a decision problem in the forms of objective, criteria, sub-criteria, and alternatives. This method offers an organized framework for establishing priorities at each hierarchical level using 1-9 scales comparisons. Exact judgements are needed when using AHP in a traditional way.

This method is commonly used in numerous MCDM problems. Its advantages are evident as demonstrated in Table 2.1. With the use of AHP method, a complex multi-criteria problem is changed into a hierarchical structure which can be used with qualitative as well as quantitative data [35, 36, 37, 38]. Bentes et al. [39] used AHP to assess the organizational performances of a telecommunications company in Brazil, focusing on performance perspectives and indicators. Ammarapala et al. [40] utilized AHP to identify potential routes in the cross-border shipment, while Kengpol et al. [8] used AHP to choose the possible freight routes between Thailand-Vietnam. Rajak and Shaw [38] combined AHP together with fuzzy TOPSIS created to create a model for the selection of health application; nevertheless, there are some limitations regarding the self-assessment bias which has an impact on internal validity.

This method offers a structured framework with the use of pairwise comparisons

Table 2.1: Comparison among different MCDA methods

MCDA method	Computational time	Simplicity	Mathematical calculations	Stability	Information type
AHP	Moderate	Very simple	Maximum	Medium	Mixed
TOPSIS	Moderate	Moderate	Moderate	Medium	Quantitative
VIKOR	Low	Simple	Moderate	Medium	Quantitative
ELECTRE	High	Moderate	Moderate	Medium	Mixed
PROMETHEE	High	Moderate	Moderate	Medium	Mixed

(1-9 scales) in order to set priorities. However, the traditional AHP requires that the experts provide exact judgments because the vagueness of their opinions can produce problematic results, Due to the complex nature of the prioritization process which is subjective, it is not easy to put an exact numerical number in pairwise comparison. For this reason, researchers usually integrate AHP with Fuzzy set theory in their studies of uncertainty situation.

2.4.2 Fuzzy set theory

In 1966, the fuzzy set theory was first put forward by Zadeh [41], focusing on the issues of uncertainty, imprecision, or ambiguity. This theory is widely known for its ability to represent ambiguous data. In order to deal with the imprecision of human decisions, this theory was introduced, with its orientation the rationality of uncertainty as a result of imprecision. The membership in a fuzzy set is a value which can be from zero to one. This theory offers a broader frame compared to the classic set theory, leading to its ability to represent the real world. A variety of studies now combine this concept together with inter-disciplinary approaches and the availability of modern technologies [38, 42].

2.4.3 Fuzzy Analytic Hierarchy Process (FAHP)

Fuzzy AHP is a systematic approach on decision-making. There have been numerous applications of this method in several fields such as risk assessment [43], production [34], and management [44]. However, there are only a few studies that concentrate on the topic of route selection. With FAHP method, the pairwise comparisons are done with linguistic variables in the form of triangular fuzzy number. The first applications of this method, and the triangular membership functions for pairwise comparisons were defined by them using Logarithmic least squares method (LLSM). Later on, the use of geometric mean for the examination and calculation of vectors in the comparison. Then, a new method which uses Arithmetic mean used in the identification of the priority vector of factors. In addition, Chang [45] also used a

Fuzzy Extent Analysis to compare matrices, deriving net weights for fuzzy comparison matrices. Wang [46] further developed the method to be called as fuzzy LLSM. Hence, Chang's best methods for the selecting routes are extend analysis methods.

2.4.4 Data Envelopment Analysis (DEA)

DEA is a methodology which is utilized in order to determine the effectiveness of decision-making units (DMUs), taking into account multiple inputs and outputs which are integrated simultaneously to solve numerous complicated problems using a ratio of the limited weight sum of outputs to the limited weight sum of inputs [9, 47, 48]. DEA has been mentioned in a variety of fields, focusing on the evaluation of service performance [48, 49, 50], hospital efficiency [51], the selection of suppliers [52], and transportation [53, 54].

Recently, several studies have used this method to examine risks in many areas. Utilizing DEA framework, Matthews [55] investigated the organization of risk management. Shi et al. [56] used it to explore the risks associated with construction in China. Skevas et al. [57] utilized it to assess farm performance.

Nevertheless, this method is a nonparametric linear programming approach which assesses the effectiveness of DMUs peers [9, 56]. The determination of the output indicators' weights is linked to Multiple Criteria Decision Making (MCDM) problem [48]. A number of MCDM methods such as Analytic Hierarchy Process (AHP) can be used to tell the weight of criteria. AHP is particularly appropriate for qualitative data with the rating score of 9 points (pairwise comparison) [47]. This can be seen in many research fields such as evaluation, selection, and forecasting [9, 21, 46]. However, since only a limited number of decision alternatives can be compared within AHP, there can be a problem when there are many other items that fail to be determined and prioritized. Moreover, considering the limitations of crisp rating scale in traditional AHP, it has shown that the experts' judgements cannot be truly expressed by crisp values. This can be solved by using Fuzzy set theory which can mathematically approach uncertainties caused by human cognitive process. The FAHP approach apply to deal with ambiguous and complicated troubles associated with decision-making process [56, 58].

So, the combination of FAHP and DEA constitutes an effective method that can be used when dealing with the multiple inputs and outputs. The bias in risk assessment can be reduced in this way. Hadi-Vencheh and Mohamadghasemi [47] applied FAHP together with DEA for the classification of multiple criteria inventories. Integrating both FAHP and DEA is easy to be done, and can be used to solve complex problems with the existence of many decision alternatives. Shi et al. [56]

used DEA and Fuzzy set theory together in order to identify the construction risks. Diouf and Kwak [52] provided a conceptual model using DEA, AHP and Fuzzy logic for selecting the suppliers.

2.4.5 Zero-One Goal Programming (ZOGP)

A MCDM methodology that is used for optimizing route selection process of multimodal transportation, particularly when a decision maker would like to achieve several objectives. This model is commonly used due to its simplicity which makes it easy for users to understand [59]. This technique serves to minimize the deviation from multiple goals when there are limited resources, which can be done by formulating the problem using this model. The model can be utilized for the selection of alternatives due to the binary nature of the selection variables and the various contradictory criteria at play. The method is a technique for MCDM when several objectives need to be achieved. The major benefit of it is its ability to address problems on a large-scale and to produce endless alternatives, giving a significant advantage when compared to other methods [33]. Nonetheless, this method cannot be applied to weight coefficients. It is usually necessary to use this method together with other ones such as AHP in order to properly weight coefficients. In this way, the weighting can be done properly with the elimination of this weakness, while retaining the ability to choose from endless alternatives [33]. Kengpol and Tuammee [9] integrated AHP together with ZOGP when trying to solve problems related to transportation. while Kim and Emery [60] and Badri et al. [61] utilized it to deal with a project selection issue.

Chapter 3

Methodology

This chapter concerns the methodologies used in this research. It proposes the framework of the selection of routes within multimodal transportation, with the application on real-world situations. A five–step conceptual framework is proposed as a way to search for the best multimodal transportation routes as shown in Figure 3.1.

3.1 Defining the scope and identifying the possible routes

The origin, destination, and the information about each route is identified. The data are gathered from interviews and brainstorming sessions with experts and providers of logistical services.

3.2 Preliminary data

Collecting data is a lengthy and costly process. That is why the quality of the data is very important. One objective of this research is to classify the factors and their interactions related to the selection of routes within multimodal transportation which are crucial in modeling-based analysis. The results of this experiment can be used within future studies. This study is based on empirical evidence related to factors related to multimodal freight transportation in Thailand. This is studied side by side with the existing literature in the field. This research uses a qualitative method

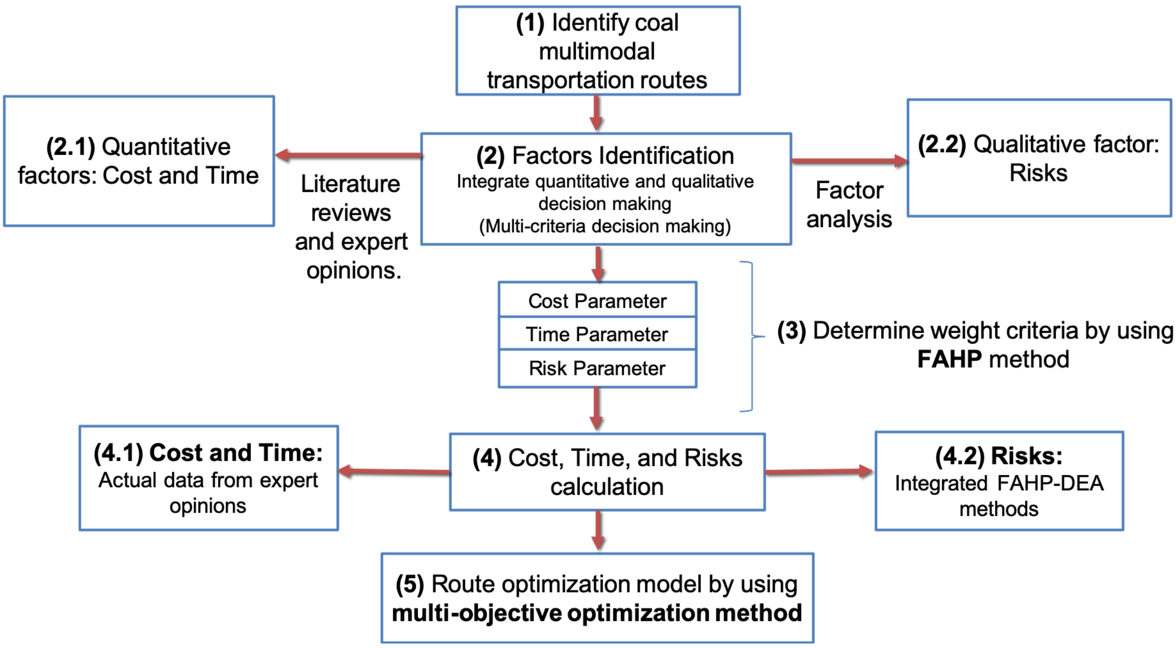


Figure 3.1: Conceptual framework for an optimal multimodal transportation route

to examine experts' opinions on how to deal with factors within multimodal transportation. Although opinions of several experts are needed within decision-making process, experts do not often see the importance of their decisions and the particularity of the decision-making transaction. The reason for this is that they do not usually have the same degree of knowledge, relevancy, and past experience. In this research, five experts with advanced qualifications in multimodal freight transportation are interviewed in order to evaluate the factors related to multimodal freight transportation in Thailand. Empirically, the first stage involved identifying factors previously studied in the past from existing literature and gathering information from in-depth face-to-face interviews with five highly skilled experts from different areas (see Table 3.1). Previous studies have shown that, there are approximately 3-6 experts who possess adequate knowledge and understanding of how best to facilitate suitability assessment which adds to the ease of operation [40].

In order to gain insight into the factors related to multimodal freight transportation, these factors were asked to be explained by the experts. Several previous research in this area of route selection have focused on the issue of cost and time minimization [6, 29]. However, not so many studies have dealt with the issue of risk minimization. Kengpol et al. [8] stated five main risk factors in the selection of routes which are political, operational, environmental, damage, equipment, and infrastructural risks. Ammarapala et al. [40] discussed six crucial factors which include risks associated with freight damage risk, cost and time of transportation, infrastructure and equipment risk, operational risk, and other factors. Based on

Table 3.1: Interview of experts in multimodal freight transportation

Experts	Organization size	Position	Role in transportation sector
Logistics company A	Large	Transportation Manager	Multimodal transportation
Logistics company B	Large	Logistics Manager	Warehouse and distribution
Logistics company C	Medium	Safety and risk manager	Risk management and control
Logistics company D	Small	Operation Manager	Logistics and shipping
Logistics company E	Small	Logistics Manager	Logistics and Transportation

the information from the interviews done by the Logistics Service Provider (LSPs), this study similarly focuses on three groups of factors related to cost, time, and risk regarding the selection of routes within multimodal transportation.

3.3 The Multiple Criteria Decision Making (MCDM) of multimodal freight transportation with quantitative and qualitative criteria

3.3.1 Quantitative data: cost and time of transportation

The quantitative data are to be presented as the results of certain actions being quantifiable in numerical terms. This research includes two kinds of quantitative cost and time in decision criteria. Several modes of transportation directly affect the cost and time of transportation. Concerning the cost of transportation, this could be grouped into fixed cost and variable cost.

Fixed costs refer to unavoidable constant transport costs which do not rise or fall depending on the size of the product being transported. These costs consist of labor costs and costs related to insurance and depreciation. On the other hand, variable costs mean those costs that are avoidable including costs related to transshipment, fuel, entry fees, handling fees, and piloting. Furthermore, there is also the geographic impact which primarily concerns distance and accessibility, being expressed as transport time. This varies considerably relying on the transportation modes and effectiveness of particular routes.

Therefore, when decisions are made when choosing transportation routes, this has a different effect on time and cost of transportation. These two types of costs are crucial within multimodal transportation. The information about these costs in each possible route was collected from the interviews with the experts in the field.

3.3.2 Qualitative data: transportation risk

Qualitative data demonstrate qualities or characteristics that can be collected through questionnaires, interviews, or observations which usually appear as a narrative or descriptive statement that can be analyzed for their patterns and meanings. Precise measurement and analysis of this type of data can be difficult. Qualitative risk analysis utilizes the probability and occurrence assessment of the risk related to the potential severity of its outcomes in order to know its overall severity. Risk analysis is a methodically way for determining the impact of process. The component of risk analysis has several phases including risk identification and risk assessment. Since risk analysis is diverse, this guarantees a wide range of appropriate techniques suitable for all situations. The processes of risk analysis concerned in this study are risk identification process and risk assessment process as shown in Figure 3.2.

- Risk Identification: The primary purpose of risk identification is to identify future uncertainties. In this study, the factor analysis are used as a statistical technique in order to classify things that show the connections between a set of interconnected variables. It is a technique that identifies a specific group of multiple qualitative factors which can be used in the process of selecting routes within a complex multimodal transportation system. This technique has been applied in many areas related to risk management areas over the past few years.

  This study incorporates the risk factors discussed in the previous studies [12, 21]. These factors and their classification were qualitatively determined using factor analysis technique in order to study the risk factors as identified in the previous studies together with the information given by the experts. These factors were then categorized and empirically validated accordingly.

- Risk assessment: Risk assessment is a way of identifying and evaluating risks. It is abundant in a range of applications within the fields of logistics and transportation. Its main purpose is to reduce the frequency of accidents by minimizing the likelihood of accidents. This study presents the risk analysis in order to identify the value of risks. It used the risk assessment in order to calculate the level of risk in any risky activities. Traditionally, in the field of transportation, the calculation can be done by multiplying the probability of accident occurrence by accident consequence as can be seen in Equation (3.1) [9]:

  $$R_{ij} = P_{ij} \times C_{ij} \tag{3.1}$$

  where R_{ij} is risk level along route segment i of multimodal route j, P is the possibility of accident occurrence along route segment i of multimodal route j

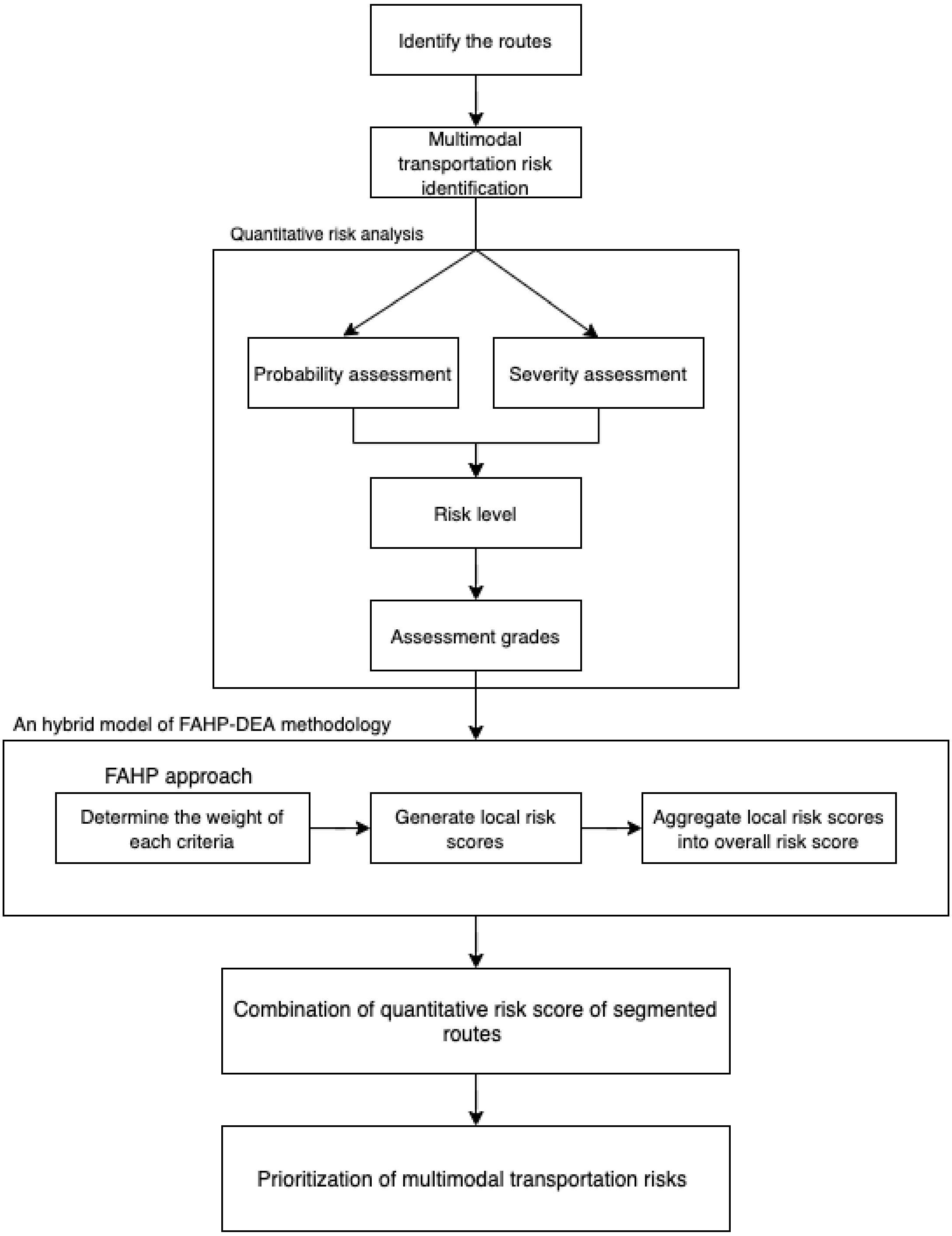


Figure 3.2: The framework of quantitative risk assessment in multimodal transportation

and C is the consequences of the accident along route segment i of multimodal route j.

Multimodal transportation is a complicated system with a wide range of risks. The causes of risks on each route may have different scores in terms of its level of risk. After this assessment, experts with high level of expertise in the field of transportation risks were asked to give opinions on the results. Consequently, the proper risk assessment model was developed taking into account different natures of risk. This multimodal transportation risk assessment is considered as a MCDM problem that have l criteria $(p = 1, .., l)$. The quantitative risk assessment derived from Equation (3.1) can be elaborated below in Equation (3.2):

$$R_{A_{ijpk}} = P_{A_{ijpk}} \times C_{A_{ijpk}} \times \triangle E_{A_{ijpk}} \tag{3.2}$$

where $R_{A_{ijpk}}$ is the risk level of segmented route i of multimodal route j for criteria p by expert k who assesses link A_{ij}. $P_{A_{ijpk}}$ is the probability assessment scale rank (1-5) of link A_{ij} for criteria p by expert k who assesses link A_{ij}. $C_{A_{ijpk}}$ is the severity impact assessment scale rank (1-5) of link A_{ij} for criteria p by expert k who assesses link A_{ij}. $\triangle E_{A_{ijpk}}$ is the ratio between distances of segmented route i and the total distance of multimodal route j for criteria p by expert k who assesses link A_{ij}.

Equation (3.2) demonstrates that the use of quantitative risk assessment to know the level of risk level of an activity that can have negative effects on people, environment, or systems. Traditionally, within the transportation risk assessment, we can calculate the level of risk by multiplying the probability of accident occurrence by the accident consequence along segmented route i of multimodal route j. This way of calculation is for when the data on accidents of multimodal logistics are not present. As such, this research introduces the probability severity impact assessment scale rank which can show the probability and impact of accident occurrence. Moreover, within the multimodal logistics, links are formed where goods transported by different modes of transportation, and nodes are formed when goods come to rest and then are transported into another transportation mode. There are several types of risk related to logistics in previous studies. The reasons for risk at nodes are not the same as those that arise along the logistics chains. This will be elaborated in following section. Furthermore, evidence has shown that there are more on bigger and longer shipping routes with different modes of transportation needed. This demonstrates that the level of risk within multimodal logistics usually depends on shipping distances and transportation modes. Nonetheless, the values of the level of risk within traditional risk assessment are shown just between different transportation modes without taking into account the shipping distances.

3.4 Risk analysis using a model of FAHP-DEA

DEA is an analytical procedure used to identify the effectiveness of DMUs with the use of multiple inputs and outputs. Many have used the combination of FAHP and DEA since they are not difficult to use and are applicable to any complicated problems that have many decision alternatives. This study builds on previous research [9, 46] with the aim to diminish bias in risk analysis.

Consider a MCDM problems with l criteria and n decision alternatives, the normalized weight vector, W_p, is obtained through pairwise comparison in the FAHP. To define the relative importance of each alternative with respect to each criterion, we construct a set of assessment grades in linguistics terms (such as very high, high, medium, low and very low) for each criterion as $G_p = \{L_{p_1}, .., L_{pk_j}\}$, $\{P = 1, .., l\}$, where, $L_{p1}, .., L_{pk_j}$ represents the linguistic terms of importance ranking from the most to the least important and k_p is the number of assessment grades for criterion P. This definition is to evaluate the different number of assessment grades and identify the relative important with respect to each criterion. Assume that criterion P is assessed by N_p experts. Then, the assessment vectors can be characterized as:

$$R(D_p(A_{ij})) = \{(L_{P_1}, NE_{ijp_1}), ..., (L_{pk_j}, NE_{ijpk_j})\} \tag{3.3}$$

where NE_{ijpk} $(k = 1, .., K_p)$ is the number of experts who assess alternative A_{ij} to grade L_{pk} under the criterion P. It is indicated that $\sum_{k=1}^{K_p} NE_{ijpk} = N_p$ for $i = 1, .., n; j = 1, .., m$.

Let $S(L_{pk})$ be the scoring of grade $L_{pk}(K = 1, .., K_p)$. Thus, the local weight of each alternative with respect to every criterion will be defined as Wang et al. and Kengpol and Tuammee [9, 46]:

$$\begin{aligned} V_{ijp} &= \sum_{k=1}^{K_p} S(L_{pk}) NE_{ijpk}, \\ \text{for} \quad & i = 1, .., n; j = 1, .., m; p = 1, .., l \end{aligned} \tag{3.4}$$

The local weight of each alternative with respect to every criterion is computed as a decision making unit (DMU), $S(L_{pk})$ as a decision variable and also the weight assigned to the output NE_{ijpk}. Thus, it can be constructed as the following DEA model with common weight [9, 46]:

$$
\begin{aligned}
&\text{Maximize} \quad \alpha \\
&\text{Subject to} \quad \alpha \leq v_{ijp} = \sum_{k=1}^{K_p} S(L_{pk}) NE_{ijpk} \leq 1, \\
&\text{for} \quad i = 1,..,n; j = 1,..,m; p = 1,..,l \\
&S(L_{p1}) \geq 2S(L_{p1}) \geq ... \geq K_p S(L_{pk_p} \geq 0)
\end{aligned} \tag{3.5}
$$

where $S(L_{p1})$,..,$S(L_{pk_j})$ are decision variables and $S(L_{p1}) \geq 2S(L_{p2}) \geq ... \geq K_p S(L_{pk_p})$ ≥ 0 is the strong ordering condition imposed on assessment grades which proposed by Noguchi et al. [62]

The local risk scores of criterion of each decision alternative can be determined in Equation (3.5). Then, the local weights of each decision alternative with respect to the l criterion is generated by Equation (3.4). Moreover, the simple additive weighting (SAW) method is utilized to aggregate the local weight into an overall weight, as follows [9, 46]:

$$
\begin{aligned}
V(A_{ij}) &= \sum_{p=1}^{l} W_p V_{ijp} \\
&= \sum_{p=1}^{l} W_p (\sum_{k=1}^{K_p} S(L_{pk}) NE_{ijpk}) \\
&\text{for} \quad i = 1,..,n; j = 1,..,m; p = 1,..,l
\end{aligned} \tag{3.6}
$$

where W_p are the criterion weights determined by FAHP methodology, $S(L_{pk})$ are the optimal scores of the assessment grades solving by Equation (3.5) and $V(A_{ij})$ are the overall weights of n decision alternatives, which the alternatives can be prioritized [9, 46].

3.4.1 Using FAHP to determine the weights of criteria

This study aims at evaluating the performance of the logistics system by constructing the potential routes taking into account the cost, time, and risk factors associated with transportation. Having reviewed the previous literature, the criteria has been set out, demonstrating the hierarchy structure. Regarding the evaluation criteria, Fuzzy AHP is used for a fuzzy hierarchical analysis in order to determine the fuzzy preference weight. Below, the notion of fuzzy hierarchical evaluation is reviewed before discussing in detail about the computational process of fuzzy AHP.

Fuzzy sets theory

Saaty [41] created a Fuzzy sets theory which is perfect for representing vague data as it is similar to human thought when using words such as approximately, nearly, very, etc. [47]. Fuzzy set refers to a set objects that have a continuum of grades of membership with a single value between 0 and 1. In this research, the multimodal transportation risk analysis is done using experts' subjective opinions together with the concept of fuzzy sets in order to determine the weight of criteria. The section below explains the fuzzy set and linguistic variables used in this research [41, 47].

Definition 1. A fuzzy set $\tilde{A}$ in a universe of discourse X is defined by a membership function $u_{\tilde{A}}(x)$ which associates $\forall x \in X$ a real number in the interval [0,1]. $u_{\tilde{A}}(x)$ express membership degree of x in $\tilde{A}$.

Definition 2. The $\alpha-$cut of fuzzy set $\tilde{A}$ is a crisp set $\tilde{A}_{\alpha} = \{x|u_{\tilde{A}}(x) \geq \alpha\}$. The support $\tilde{A}$ is the crisp set $Supp(\tilde{A}) = \{x|u_{\tilde{A}}(x) \geq 0\}$. $\tilde{A}$ is normal if and only if $Supp_{x\in X} u_{\tilde{A}}(x) = 1$.

Definition 3. A fuzzy subset $\tilde{A}$ of universe set X is convex if and only if $u_{\tilde{A}}(\lambda x + (1-\lambda)y) \geq \min(u_{\tilde{A}}(\mathrm{x}), u_{\tilde{A}}(\mathrm{y}))$, $\forall x, y \in$ X, $\lambda \in$[0,1], where min denotes the minimum operator.

Definition 4. $\tilde{A}$ is a fuzzy number if and only if $\tilde{A}$ is a normal and convex fuzzy set of R.

Definition 5. A triangular fuzzy number (TFN) $\tilde{A}$ is defined with piece-wise liner membership function $u_{\tilde{A}}$(x) as follows:

$$u_{\tilde{A}}(x) = \begin{cases} \dfrac{x-l}{m-l} & , l \leq x \leq m, \\ \dfrac{u-x}{u-m} & , m \leq x \leq u, \\ 0 & , otherwise, \end{cases} \tag{3.7}$$

And as a triplet (l, m, u) is indicated, where l, u the lower and upper bound respectively, and m is the most likely value of $\tilde{A}$.

Definition 6. Let $\tilde{A} = (l_1, m_1, u_1)$ and $\tilde{B} = (l_2, m_2, u_2)$ be two positive triangular fuzzy numbers and r be a positive real number. Then sum, subtraction, multiplication, distance and inversion of these two triangular fuzzy number is defined as follows:

$\tilde{A} \oplus \tilde{B} = [l_1+l_2,\ m_1+m_2,\ u_1+u_2]$,

$\tilde{A} \ominus \tilde{B} = [l_1\text{-}l_2,\ m_1\text{-}m_2,\ u_1\text{-}u_2]$,

$\tilde{A} \otimes \tilde{B} = [l_1 \times \mathrm{l}_2,\ m_1 \times \mathrm{m}_2,\ u_1 \times \mathrm{u}_2]$,

$d(\tilde{A}, \tilde{B}) = \sqrt{\frac{1}{3}[l_1 - l_2]^2 + [m_1 - m_2]^2 + [u_1 - u_2]^2}$,

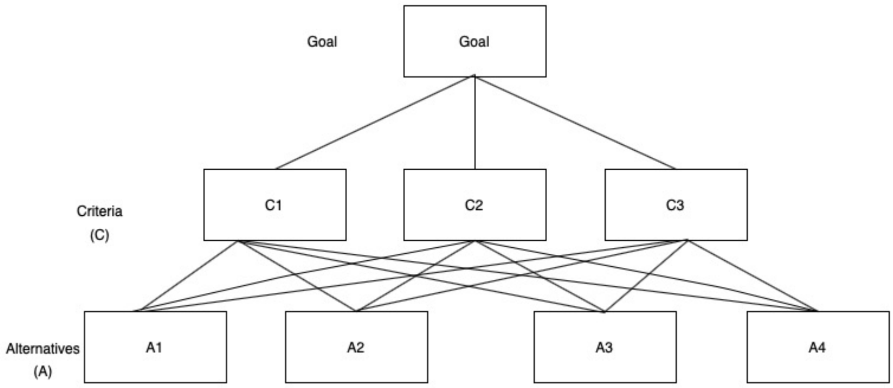


Figure 3.3: The hierarchy structure of decision

$\tilde{A}\otimes$r$= [l_1, m_1, u_1]$,
$(\tilde{A})^{-1} = (\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1})$.

Fuzzy AHP (FAHP)

The AHP, which is considered as a crucial MCDM technique used to solve complicated problems, was introduced by Saaty [41]. It compares a set of judgments and identify the importance weight of each judgement [48]. AHP consists of three steps which are:

- Building the hierarchical structure of decisions (Figure 3.3).
- Determining the weight of criteria for each hierarchical level.
- Aggregating the normalized weights to obtain the final scores.

Nevertheless, it is not easy to use traditional AHP when dealing with vague problems, and this gap can be reduced with the use of fuzzy AHP which helps solve these vague problems. This can be done by performing the pairwise comparisons of criteria and alternatives via linguistic variables presented in the form of triangular fuzzy number. Many studies have applied FAHP on vague data. Chang [45] used the extent analysis method which prioritizes the weights to achieve computational simplicity [9]. This similar method is also used in this research, deriving crisp weights for fuzzy comparison matrices. The experts would examine the pairwise judgment matrices and their weights would then be assessed in linguistic terms which are then converted into TFNs using the scale as demonstrated in Table 3.2. The algorithm of this method is illustrated below.

Table 3.2: Fuzzy linguistic scale

Uncertainty judgement	Triangular fuzzy scale	Triangular reciprocal scale
Equally important	(1,1,1)	(1,1,1)
Weakly important	(2,3,4)	(1/4,1/3,1/2)
Fairly important	(4,5,6)	(1/6,1/5,1/4)
Strongly important	(6,7,8)	(1/8,1/7,1/6)
Absolutely important	(9,9,9)	(1/9,1/9,1/9)

Let $x = \{x_1, x_2, ..., x_n\}$ be an object set, and U $= \{u_1, u_2, ..., u_m\}$ be a goal set. According to method of Chang [45] extend analysis, each object is taken and extend analysis for each goal, g_i is performed respectively. It means that it is possible to obtain the values of m extent analyses that can be demonstrated as $M_{gi}^1, M_{gi}^2, \ldots, M_{gi}^m$, $i = 1, 2, ..., n$ where all the M_{gi}^j $(j = 1, 2, .., m)$ are TFNs.
The step of Chang's extent analysis can be given as in the following:
Step 1. The value of fuzzy synthetic extent with the respect to the i^{th} object is defined as:

$$S_i = \sum_{j=1}^{m} M_{g}^{j}{}_{i} \bigotimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g}^{1}{}_{i} \right]^{-1} \tag{3.8}$$

To obtain $\sum_{j=1}^{m} M_{g}^{1}{}_{i}$ performed the fuzzy addition operation of m extend analysis values for a particular matrix such that

$$\sum_{j=1}^{m} M_{g}^{j}{}_{i} = [\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} m_j, \sum_{j=1}^{m} u_j] \tag{3.9}$$

and to obtain $\sum_{i=1}^{m} \sum_{j=1}^{m} M_{g}^{j}{}_{i}$, performed the fuzzy addition operation of $M_{g}^{j}{}_{i}(j = 1, 2, ..., m)$ values such that

$$\sum_{i=1}^{m} \sum_{j=1}^{m} M_{g}^{j}{}_{i} = [\sum_{j=1}^{n} l_i, \sum_{j=1}^{n} m_i, \sum_{j=1}^{n} u_i] \tag{3.10}$$

The inverse of the vector in Equation (3.10) can be computed as:

$$\left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g}^{j}{}_{i} \right]^{-1} = \left[\frac{1}{\sum_{j=1}^{n} u_i}, \frac{1}{\sum_{j=1}^{n} m_i}, \frac{1}{\sum_{j=1}^{n} l_i} \right] \tag{3.11}$$

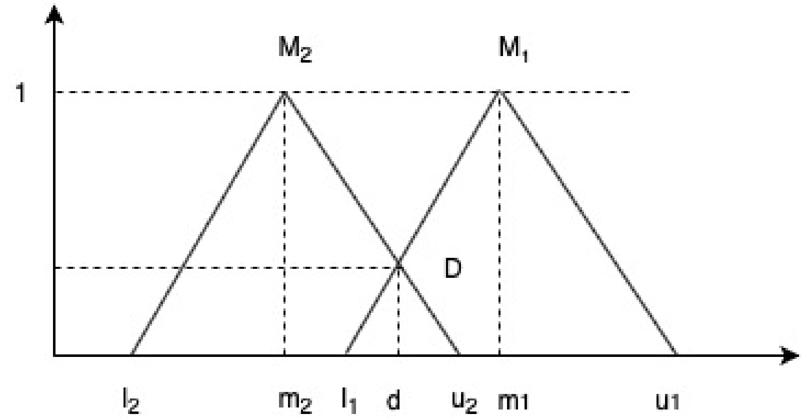


Figure 3.4: The interaction between $M_1$and M_2

Step 2. The degree of possibility of $M_2 = (l_2,\ m_2,\ u_2)$ and $M_1 = (l_1,\ m_1,\ u_1)$ is defined as:

$$V(M_2 \geq M_1) = \sup_{y \geq x} \lfloor min(\mu_{M1}(x), \mu_{M2}(y)) \rfloor \tag{3.12}$$

and can be equivalently expressed as follows:

$$\begin{aligned} \mathrm{V}(\mathrm{M}_2 \geq M_1) &= \mathrm{hgt}(\mathrm{M}_1 \cap M_2) = \mu_{M2}(d) \\ &= \begin{cases} 1 & m_2 \geq m_1 \\ 0 & l_1 \geq u_2 \\ \frac{l_1 - u_2}{(m_2 - u_2) - (m_1 - l_1)} & otherwise \end{cases} \end{aligned} \tag{3.13}$$

where d is the ordinate of the highest intersection point D between μ_{M1} and μ_{M2} (See in Figure 3.4)

To compare M_1 and M_2, we need both the values of $V(M_2 \geq M_1)$ and $V(M_1 \geq M_2)$.
Step 3. The degree possibility for a convex fuzzy number to be greater than k convex fuzzy numbers M_i $(i = 1, 2, ..., k)$ can be defined as,

$$\begin{aligned} &V(M \geq M_1, M_2, ..., M_k) \\ &= V[(M \geq M_1) and (M \geq M_2] and ... and (M \geq M_k)] \\ &= min V(M \geq M_i), i = 1, 2, 3, ..., k \end{aligned} \tag{3.14}$$

Assume that,

$$d'(M_i) = min V(M_i \geq M_k) \tag{3.15}$$

For $k = 1, 2, ..., n$ and $k \neq 1$. The weight vector can be given by the following formula:

Table 3.3: Random Index (RI) of random matrices

N	3	4	5	6	7	8	9
$RI(n)$	0.58	0.90	1.12	1.24	1.32	1.41	1.45

$$W' = (d'(M_1), d'(M_2), ..., d'(M_n))^T \tag{3.16}$$

Step 4. Normalization step, the normalized weight vectors and results are a non-fuzzy numbers which are given as:

$$W = (d(M_1), d(M_2), ..., d(M_n))^T, \tag{3.17}$$

Where W is a non-fuzzy number
Step 5. To defuzzify the fuzzy weight, we used the the graded mean integration approach, where TFNs, $P = (l,\ m,\ u)$ could be difuzzified to a crisp number as follows:

$$P_{crisp} = \frac{(4m + l + u)}{6} \tag{3.18}$$

Step 6. It is important to check the consistency index between the pairwise matrices. The consistency ratio (CR) is defined as the ratio between the consistency of an evaluation index (CI) and the consistency of a random index (RI). Consistency ratio (CR) is calculated by Equations (3.19)-(3.20):

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{3.19}$$

where λ_{max} is the largest eigenvalue of the comparison matrix, and n is the dimension of the matrix.

$$CR = \frac{CI}{RI(n)} \tag{3.20}$$

where $RI(n)$is a random index that depends on n, RI as shown in Table 3.3.

The acceptance limit of CR is 0.1 or 10%. if it is not less than 0.1, the judgment needs to be carried out the pairwise comparison again to make the decision more consistent.

3.5 Optimization with the use of ZOGP

The Zero-One Goal Programming (ZOGP) is an easy-to-use method for optimizing the route selection within the multimodal transportation. It is the MCDM technique which is frequently used when there are many goals to achieve [59]. When there are limited resources, this ZOGP technique is chosen as a way to reduce deviation from multiple objectives, with problems being framed with the use of this model. With this model, the alternatives can be selected due to of the binary nature of the selection variables, together with several conflicting criteria in consideration. In this study, since the aim is to use a multi-objective optimization approach to search for the best multimodal transportation routes, ZOGP was chosen to solve large-scale problems with complex data.

The route selection model in this research incorporates FAHP together with the multi-objective optimization approach. The significance weights taken from FAHP together with the parameters and data from previous studies are used in order to identify the objective function and constraints. The purpose of the objective function is for choosing the best multimodal freight transportation route with the lowest cost, time, and level of risk. The model's formula is demonstrated in Equations (3.21)-(3.36). The needs and desires of the users were incorporated with the ZOGP. The chosen route is the one with the smallest total deviation which have three layers as stated below.

The needs and desires of the users were incorporated with the ZOGP. The chosen route is the one with the smallest total deviation which have three layers as stated below.

The highest layer: objective function

ZOGP has the objective functions which are combined together with the weights from FAHP is order to lower the deviation in Equation (3.21). The transport budget is the first objective, following by transport time, and five multimodal transportation risks. The significance weights are identified by users with the use of FAHP.

$$Minimize \quad Z_i = \quad w_c(d_c^+) + w_t(d_t^+) + w_z(d_z^+(z')) \tag{3.21}$$

Where
Z_i = The total deviation of objective or main decision criteria for i^{th} route
w_c = The relative weight of cost's objective
w_t = The relative weight of time's objective
w_z = The relative weight of risks' bjective
d_c^+ = The overachievement deviation of cost.
d_t^+ = The overachievement deviation of time
$d_z^+(z')$ = The overachievement deviation of risks

The second layer: constraint function of cost, time, and risk

Equation (3.22) demonstrates the deviation between the cost and the budget, with the first not higher than the latter. Equation (3.23) shows the time constraint function highlighting the deviation between transport time and its lead time limit, with the first not exceeding the latter.

Equation (3.24) demonstrates the deviation between the deviation of the scores of the freight transportation risk and the maximum deviation of route scores. The routes that have the lowest scores have zero deviation. The following section demonstrates the constraints related to this model.

$$c_1x_1 + c_2x_2 + c_3x_3 + ... + c_nx_n - d_c^+ \leq \text{C} \tag{3.22}$$

$$t_1x_1 + t_2x_2 + t_3x_3 + ... + t_nx_n - d_t^+ \leq \text{T} \tag{3.23}$$

$$z_1'x_1 + z_2'x_2 + z_3'x_3 + ... + z_n'x_n - d_z'^+ \leq \text{Max z'} \tag{3.24}$$

Where
x_i = The zero-one variables representing the non-selection (zero) or selection (one) of route i = 1, 2, 3,..., n, subject to criteria right hand side (cost, time and risks)
c_i = The coefficient of x_i in transport cost constraint for i^{th} route
t_i = The coefficient of x_i in transport time constraint for i^{th} route
z_i' = The coefficient of x_i in transport standard risk constraint for i^{th} route
C = The percentage of transport cost limited by user
T = The percentage of transport time limited by user

Nevertheless, the objective functions data were converted to percentages since they were recorded in different units of evaluation. Equations (3.25)–(3.28) demonstrate the normalization.

c_i = The coefficient of x_i in budget constraint that is cost of each route in percentage of the under budget:

$$c_i = \frac{\text{(Budget limited by user)} - \text{(Cost of route } i\text{)}}{\text{Budget limited by user}} \times 100 \tag{3.25}$$

C = The right-hand side of Equation (3.22) is percentage of budget limited by user that is presented below:

$$C = \frac{\text{(Budget limited by user)} - \text{(Minimum cost of route } i\text{)}}{\text{Budget limited by user}} \times 100 \tag{3.26}$$

t_i = The coefficient of x_i in transport time constraint that is a percentage of transport time of each route which is limited by user:

$$t_i = \frac{\text{Transportation time of route } i}{\text{Transportation time limited by user}} \times 100 \tag{3.27}$$

T is the percentage of transport time limited by user (=100%)

z_i = The coefficient of x_i in standard risk constraint that is a percentage of transport risk of each route which is limited by user:

$$z' = \frac{\text{(The maximum deviation of standard risk score)} - \text{(The deviation of standard risk for } i \text{ route)}}{\text{The maximum deviation of standard risk score}} \times 100 \tag{3.28}$$

To obtain z'_i one must sum up the deviation of standard risks, this is defined as:

$$z'_i = \quad w_{r1}(d^-_r{}_1) + w_{r2}(d^-_r{}_2) + w_{r3}(d^-_r{}_3) + ... + w_{rm}(d^-_r{}_m) \tag{3.29}$$

Where
w_{rk} = The relative weight of risk scores for k^{th} of risks
d^-_{rk} = Under achievements deviation of risk scores for k^{th} of risks
k = The k^{th} of risks; k = 1,2,3,...,m

The lowest layer: constraint function of sub-criteria risk scores

The constraint functions of sub-criteria risk potential scores demonstrate the deviation between possible scores for each kind of risk and the users-determined potential scores. The routes that have the highest potential scores that are higher than or equal to the acceptable potential scores have zero deviation. On the other hand, the other routes with potential score higher than or equal to the acceptable scores, their deviations would depend on their scores.

For this third layer of ZOGP, those routes that have lower the potential scores than the acceptable route scores are not taken into consideration. Constraint function of the road freight transportation sub-criteria risk scores can be demonstrated below.

$$r_1x_1 + r_2x_2 + r_3x_3 + ... + r_{kn}x_n - d_{rk}^{-} \leq R_k \tag{3.30}$$

In equations (3.31)–(3.34), controls are established in order to make sure that only a single route is optimal for a particular situation. If the cost, time, and risk are higher than the limits defined by the users, that route will not be disregarded.

$$x_1 + x_2 + ... + x_n = 1 \tag{3.31}$$

$$w_c(d_c)^+, w_t(d_t)^+, w_z(d_z^+(z')), w_{rk}(d_k^-) \geq 0 \tag{3.32}$$

$$c_i, t_i, z_i', r_{ki} \geq 0 \text{ for } i \ = 1, 2, ..., n \tag{3.33}$$

$$x_i = \ 0 \text{ or } 1; i = 1, 2, ..., n \tag{3.34}$$

Since there are different units of evaluation within the sub-criteria risk scores, r_{ki} needs to be normalized. This can be done by calculating the difference between the possible scores in each route and its acceptable scores which have a positive correlation. The higher the potential scores, the higher the r_{ki} will be, as demonstrated in equations (3.35)- (3.36).

r_{ki} = The coefficient of transportation risk constraints:

$$r_{ki} = \frac{\text{(Risk score limited by user)} - \text{(Risk score of route } i\text{)}}{\text{Risk score limited by user}} \times 100 \tag{3.35}$$

R_k = The right-hand side of transportation risk constraints in Equation (3.36):

$$R_k = \frac{\text{Risk score limited by user} - \text{Minimum risk score of route } i}{\text{Risk score limited by user}} \times 100 \tag{3.36}$$

Chapter 4

Case study and Analysis

The system of multimodal freight transportation provides a diverse range of services to many industries. Coal is the main nonperishable commodity being transported for regional power production and other industries including paper industry, cement industry, and those which need high heat in production. It is normally transported by boats, trains, or cars from Indonesia into Thailand, with waterway as the main route of transportation (Appendix A). It is probable that the use of coal will increase in the future. Coal, as the cheapest resource for generating heat, is used by the Electricity Generating Authority of Thailand (EGAT) as an alternative resource for electricity generation.

The primary objective of this study is to improve the performance of the logistics system by searching for the best route that would minimize the negative factors at play. The combination of methodologies is applied including FAHP, DEA, and multi-objective optimization. This section discusses the five-phase framework for the selection of the best routes within the multimodal freight transportation.

4.1 Scope of case study

This section explains the conceptual framework of this research which concerns the route selection strategy in the system of multimodal transportation, with the case study which focuses on the freight routes (consisting of 3 modes of transportation: railway, waterway, roadway) from Srichang in Chonburi Province to a cement industry in Saraburi Province, Thailand. In each route, the capacity limit is set at 50,000 tons. The data were derived the experts in the field and the logistics service providers (LSPs) who were interviewed. In order to identify the scope of this

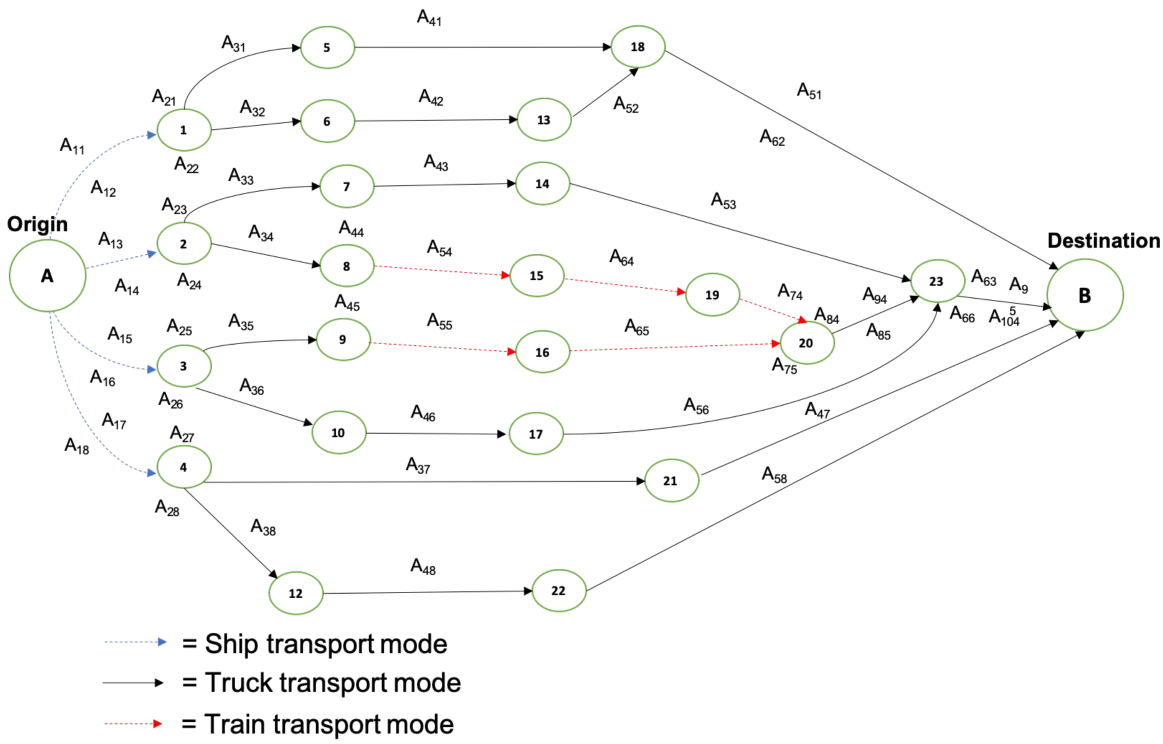


Figure 4.1: Network for case study

research and the potential routes within the system of multimodal transportation, the researcher interviewed five experts who can be categorized into three groups regarding their areas of expertise within the coal industries. After the interviews and the brainstorming sessions, eight potential routes were identified, all of which combine several transportation modes. In this study, the process of choosing the best route(s) concerns the analyses of the multi-criteria including cost, time, and risk associated with transportation.

The data on the possible multimodal routes for coal transportation in Thailand together with the opinions of decision makers were used for the modeling. This in order to identify the scope of the research and search for the best routs. Eight possible routes, each combining different transportation modes (e.g. rail, sea and road), are taken into consideration as demonstrated in Figure 4.1 and Table 4.1 (more details can be found in Appendix B).

Table 4.1: The possible multimodal transportation routes

Routes	Paths	Transport mode
1	A-1-5-18-B	Ship and truck
2	A-1-6-13-18-B	Ship and truck
3	A-2-7-14-23-B	Ship and truck
4	A-2-8-15-19-20-23-B	Ship, train and truck
5	A-3-9-16-20-23-B	Ship, train and truck
6	A-3-10-17-23-B	Ship and truck
7	A-4-21-B	Ship and truck
8	A-4-12-22-B	Ship and truck

4.2 Quantitative data: cost and time of transportation

The quantitative data on the cost and time of transportation in this research show the outcomes in numeric terms of particular actions. The modes of transportation directly determine the cost and time.

Concerning transportation cost, there are two types of it which are fixed cost and variable cost. Fixed costs are unavoidable and constant no matter what size of the product being transported. For example, the labor, depreciation and insurance costs are considered fixed costs. On the other hand, variable costs are avoidable including the costs of transshipment, fuel, entry fees, and pilotage. Furthermore, regarding the geographical impact, distance and accessibility are considered, expressing in terms of the time used which varies considerably depending on different modes of transportation and the effectiveness of particular transportation routes.

In this study, the transportation cost components not only concern roadways, railways, inland waterways, seaways, but also multimodal points of transfer including ports, rail-freight terminals, and inland clearance depots. When calculating the prices of all these modes of transportation, several factors are considered. Beside costs of container and customs clearance, the costs vary by mode of transportation. The final costs are affected by different freight rates of each mode, the frequency of the routes, and the extra fees including the fuel cost and other costs related to transport procedures.

These are internal costs assumed by the transport services providers. They can be divided into two types which are fixed costs (infrastructural) and variable costs (operational), depending on different conditions associated with geographical factors, infrastructural factors, fuel costs, administrative barriers, and modes of transportation. Other factors that impact transportation costs are associated with shipments and the friction of distance. The following components are what have to be taken into account when calculating freight cost per trip for each mode of transportation.

4.2.1 Ship Freight Rates

Sip frights rates are set by shipping companies depending on the sizes of containers. These rates concern extra costs including fuel cost and other seasonal and regional costs, changing each month depending on the market prices.

Terminal Handling Charges

These are the costs paid when containers are unloaded to the harbor terminal from the ship. Most of the time, these costs do not change according to the sizes of containers used, meaning that those who use big containers for high-volume goods would have a big advantage.

Delivery

Containers have to be transported from the terminal to the customer's storage location, and there are many transport options such transporting by lorries, trains, or barges. The most convenient mode would be selected by the logistics provider depending on the area and the level urgency.

4.2.2 Truck Freight Rates

These rates are set by the trucking companies and are readjusted periodically according to the market prices and demand-supply factors. In other words, the routes that are in high demand are usually cheaper than those that are in low demand. This cost is crucial when calculating the costs of transportation.

Pick-up

Normally, the products are storage directly from the customers and are taken to a warehouse location. There are costs that have to be paid along the way including and the costs of fuel, toll, and staff, which affect the total truck transport costs.

Handling

If a cargo is shipped, it will be taken to a warehouse where it is handled. The goods inside are sorted depending on route and urgency, and are loaded onto the trucks. The costs incurred at this point is the costs of staff who handle, plan, and execute the process of sorting and (un)loading the goods. There is no cost of handling when shipping a whole container since the goods are brought directly to their destination via truck.

Main leg

This refers to the costs of actual transportation which can be calculated by adding the costs of the route together with the incidental costs including fuel, toll, and regional as well as seasonal charges. This depends on the market prices and the decisions of each trucking company.

Delivery

From the warehouse, the goods have to be taken to the actual destination. The costs incurred are those associated with transportation to and from the destination and the handling cost.

4.2.3 Rail Freight Rates

Freight rates are usually calculated based on volume or weight, but for rail freight costs, these rates are usually calculated per pallet. Usually, less than Container Load (LCL) containers are the cheapest option.

Table 4.2: Database of transportation cost, transportation time and distances

Route	Time (hrs.)	Cost (dollars)	Distances (km.)
1	73	120.26	212
2	75	121.70	210
3	73	125.93	211
4	168	113.50	261
5	140	115.15	260
6	75	117.86	192
7	85	120.10	208
8	80	118.50	204

Rail Terminal Costs

There are several types of costs to be considered at a rail terminal such as loading and unloading costs from one transportation mode to another, taking into account lead time and safety factors.

Delivery

As the rail freight is expected to reach its destination quickly and cheaply, a truck is often used for its low cost, small lead time, and high level of safety. The transportation mode is selected by the provider depending on region and urgency.

The geographical effects are primarily associated with distance and accessibility. One of the most crucial factors that affect the costs of transportation is distance. The harder it is to exchange space for a cost, the more significant the friction of distance is. Distance can be articulated in terms of length of distance, duration of distance, or the amount of energy needed, which greatly depend on different modes of transportation and the efficiency of particular routes. The geographical impact on the cost structure can also concern rate zones at the local level, national level, and the international level. Transport time is an important factor that must be considered together with the frequency, the order time, and punctuality. Different multimodal transportation routes affect cost and time of transportation in different ways. Fixed and variable costs are taken into consideration in the analysis together with the time and cost data of transportation for possible route from the interviews with the experts in the field. The results are demonstrated in Table 4.2.

Table 4.3: Experts' qualification

No.	Experts	Experience (years)	Position
1	Company A	32	CEO, Transport Manager
2	Company B	25	Logistics Manager
3	Company C	20	Safety and risk manager
4	Company D	21	Operation Manager
5	Company E	20	Consultant
6	Company F	24	Consultant
7	Technical office A	30	Bureau of Traffic Safety
8	Technical office B	35	Bureau of Road Maintenance
9	Technical office C	23	Chief Engineer
10	Technical office D	31	Engineer

4.3 Qualitative data: transportation risk

In the process of analyzing transportation risk, the impact and occurrence of human activities with hazardous characteristics are evaluated, constituting a crucial tool for the design of safety policy [28]. Risk identification is considered the first step when analyzing the nature of risks incurred in the system of multimodal transportation.

4.3.1 Risk identification

This research uses a face-to-face interview approach together with the review of previous literature in order to qualitatively identify the risk factors. The interviewees (academic researchers, logistics and shipping managers) are experts who have objective views on transportation risk and are directly involved in transportation and logistics management for longer than 20 years (Table 4.3).

4.3.2 Factor analysis

Factor Analysis (FA) is well-known main tools of the multivariate statistics for data analysis. Generally, Likert scales of measurements are considered, and it is shown variables correlations and variances are connected to the mean values. FA defined by subsets of highly related variables can correspond to the lower levels of Likert scales meaning the absence of the measured features, thus these loading vectors could be senseless for interpretation.

This is a statistical technique for describing variability of correlated variables, while shrinking a mass of data into a smaller and more manageable data set that is

Total Variance Explained

Component	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	2.020	16.830	16.830	2.020	16.830	16.830	1.734	14.453	14.453
2	1.491	12.421	29.251	1.491	12.421	29.251	1.476	12.303	26.756
3	1.306	10.887	40.138	1.306	10.887	40.138	1.430	11.920	38.676
4	1.179	9.823	49.961	1.179	9.823	49.961	1.245	10.372	49.048
5	1.079	8.992	58.953	1.079	8.992	58.953	1.189	9.905	58.953
6	.997	8.308	67.262						
7	.884	7.364	74.626						
8	.846	7.051	81.677						
9	.639	5.325	87.002						
10	.596	4.968	91.970						
11	.516	4.299	96.269						
12	.448	3.731	100.000						

Extraction Method: Principal Component Analysis.

Figure 4.2: Total variance description

easier to understand. Factor analysis leads us to know the hidden patterns and how they overlap, revealing the characteristics behind those patterns.

In this study, 12 risk factor items are included and these items are determined using information from the previous studies together with the interviews with the experts in the transportation field. Then the sample size with 200 samples from logistics and transportation companies were observed according to a minimum of 10 observations per variable which is necessary to avoid computational difficulties. After that the questionnaire with a 5-point Likert scale is used in this study in order to know the significance of each factor concerning multimodal transportation (Appendix D). Finally, SPSS program is implemented to interpret the risk factor loading.

Reliability of data

Since the size of survey data in this research is large (200 samples), Cronbach's coefficient alpha is utilized to measure the reliability of data, with the result of the coefficient of Cronbach's alpha being nearly 1 (0.880), indicating that there is an acceptable level of reliability of data in this research.

Relationship of factors when selecting multimodal transportation routes

The Pearson correlation is commonly utilized to identify the connections of each factor [21]. This research also uses it to identify relationships of all factors associated with the process of selecting multimodal transportation routes. In this research,

Component Transformation Matrix

Component	1	2	3	4	5
1	.816	.162	-.528	.003	.170
2	.018	.927	.235	-.170	-.236
3	-.328	.283	-.373	.810	.132
4	.212	.075	.592	.211	.745
5	.426	-.168	.421	.520	-.585

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.

Figure 4.3: Component transformation matrix

Factor Analysis

Correlation Matrix

		Lack o fmultimodal equipment	Damages in transportation	Accident rate	Fire	Natural disaster	Traceability on reverse logistics	Lack of skilled workers	Demand volatility	On-time/on-budget delivery	Infrastructure limitations	Route restrictions	Cargo being stolen or tampered
Correlation	Lack o fmultimodal equipment	1.000	.058	.082	-.115	-.117	.002	.056	.070	.081	.051	.144	-.049
	Damages in transportation	.058	1.000	-.013	-.071	.067	.133	-.083	-.045	.009	-.295	-.101	-.059
	Accident rate	.082	-.013	1.000	.023	.119	-.209	-.046	.154	-.061	.279	.485	.082
	Fire	-.115	-.071	.023	1.000	-.087	-.042	.065	-.036	-.051	-.023	-.041	.184
	Natural disaster	-.117	.067	.119	-.087	1.000	-.156	.051	-.065	-.121	.027	.100	.076
	Traceability on reverse logistics	.002	.133	-.209	-.042	-.156	1.000	-.086	-.099	.006	-.285	-.119	.010
	Lack of skilled workers	.056	-.083	-.046	.065	.051	-.086	1.000	.068	.132	-.136	.085	.016
	Demand volatility	.070	-.045	.154	-.036	-.065	-.099	.068	1.000	.337	.108	.174	-.018
	On-time/on-budget delivery	.081	.009	-.061	-.051	-.121	.006	.132	.337	1.000	-.134	.047	.097
	Infrastructure limitations	.051	-.295	.279	-.023	.027	-.285	-.136	.108	-.134	1.000	.237	.031
	Route restrictions	.144	-.101	.485	-.041	.100	-.119	.085	.174	.047	.237	1.000	.003
	Cargo being stolen or tampered	-.049	-.059	.082	.184	.076	.010	.016	-.018	.097	.031	.003	1.000

Figure 4.4: Correlation matrix

factor analysis is used for grouping factor components. Several indices such as the KMO (Kaiser–Meyer–Olkin) measure which is a measure of sampling adequacy and the Bartlett's test of sphericity are investigated in Figure 4.5. In this research, the value of KMO is 0.549, meaning that the sample is suitable for a factor analysis (the value should be higher than 0.5 for it to be adequate for the analysis). The Bartlett's test of sphericity is used to test the assumption that both the variance matrices and the covariance matrices are identity matrices which have ones in the diagonal and zeros in the off-diagonal. If so, the variables are considered as totally unrelated the data is not suitable for a factor analysis. In this research, the Bartlett's test of sphericity is presented as $\chi^2 = 216.38$ ($df = 66$), which means that is it appropriate to use a factor analysis in this research.

KMO and Bartlett's Test

Kaiser-Meyer-Olkin Measure of Sampling Adequacy.		.549
Bartlett's Test of Sphericity	Approx. Chi-Square	216.380
	df	66
	Sig.	.000

Figure 4.5: KMO and Bartlett's Test

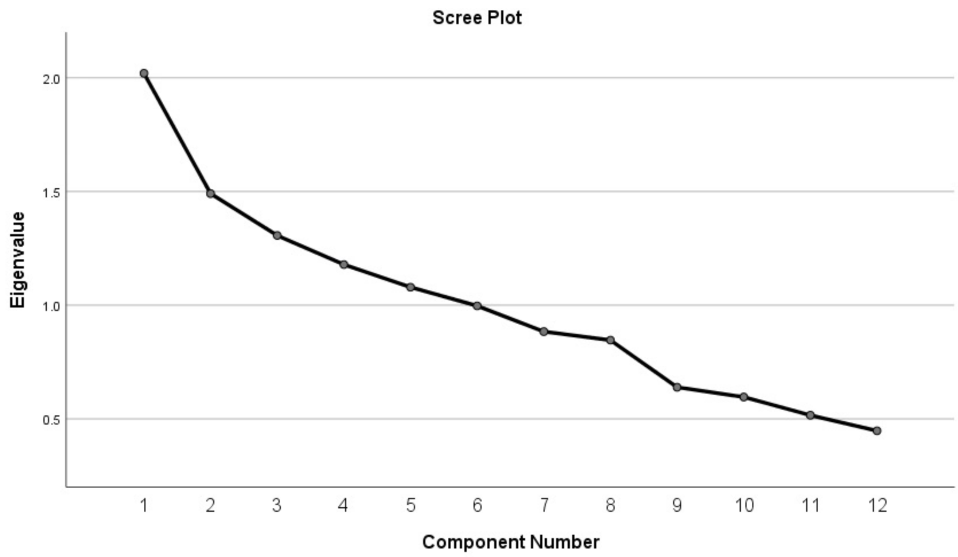


Figure 4.6: Factor analysis plot

Factor extraction factor components

According to Figure 4.2 and Figure 4.3, the first factor (out of five factors) has the eigenvalue of >1, and is extracted with around 60% of the variance explained. As the eigenvalue of the sixth factor is 0.997 (< 1), and as it would add an extra of 9.997% of variance, the second analysis (Rotation Sum of Squared Loadings) is accomplished, forcing the extraction of five factor components. Nevertheless, the analysis of the third extracted factor using varimax rotation reveals that there are five variables on that specific factor (not a common factor). Given that each factor must have at least five items in order to remain a common factor, the initial analysis is retained with the cluster of five factors.

Table 4.4: Factor loading and factor grouping construct

Multimodal transportation risk factors	Factor loading
1. Risk of infrastructure and equipment	
1.1 Accident rate	0.825
1.2 Route restrictions	0.741
1.3 Infrastructure limitations	0.423
1.4 Lack of multimodal equipment	0.308
2. Operational risk	
2.1 On-time/on-budget delivery	0.780
2.2 Demand volatility	0.641
2.3 Lack of skilled workers	0.520
3. Freight damaged risk	
3.1 Damages in transportation	0.785
3.2 Traceability on reverse logistics	0.515
4.Security risk	
4.1 Cargo being stolen or tampered	0.755
4.2 Fire	0.731
5.Environmental risk	
5.1 Natural disaster	0.772
5.2 Climate changes	0.623

Grouping factors into clusters

All the factors are classified using principal component analysis, with each factor loading representing the correlation of a factor and a variable. A positive loading means an activation of a factor, while a negative loading means a lack of factor activation. With the varimax method of orthogonal rotation, uncorrelated factors are derived and factor interpretation is simplified. Table 4.4 shows clusters of components. For instance, the rate accident, route restrictions, infrastructural limitations, and lack of multimodal equipment are grouped together into a cluster called risk of Infrastructure and Equipment, while operational risk is another cluster which includes on-time/on-budget delivery, demand volatility, and lack of skilled workers.

Testing the validity and reliability of data and content

Scale factor analyzes are used to check if each set of items is a valid indicator, with the results demonstrated in Figure 4.4, Figure 4.6, and Table 4.4. The factor loadings vary from 0.515 to 0.825, exceeding the recommended minimum value of 0.5. All items within each scale are loaded on one factor, implying that each factor is valid as a construct.

To summarize, 12 qualitative factors can be grouped into 5 clusters as stated below. These clusters are validated in the multimodal transportation context. The factors will be classified according to the attributes below.

- Freight damaged risk: this is the risks associated with damage or loss of products when they are transferred and delivered [8, 9].
- Infrastructure and equipment risk: this concerns the risks associated with, for instance, road and railway density, facility of equipment, handling of materials, and transit utilization [9].
- Operational risk: this includes the risks associated with, for instance, documents and contracts, strikes, the lack of skilled workers, and server system errors [9].
- Security risk: this means the risks within the overall transportation security planning such as theft from an insider and other types of accidents such as fire and terrorism.
- Environmental risk: this is the risks from natural phenomenon such as from floods and storms, natural disasters, and climate changes.

4.3.3 Risk analysis

Risk analysis is used to identify and assess the risk. It is commonly used in the fields of logistics and transportation with the primary purpose of reducing the possibility of the occurrence of the risk.

The data of multimodal transportation routes of coal transportation from Srichang to the Cement industry in Saraburi province are collected by the author. The information of different modes of transportation is collected from interviews with the experts. Figure 4.1 demonstrates 8 possible multimodal logistics routes.

In Table 4.5, which shows the detail of segmented route in, route A11 refers to the route from Srichang to Pasak river with ship as the mode of transportation. A21 refers to the route from Pasak river to Nakornluang Port with ship as the mode of transportation. A31 (Nakornluang Port) is the point where modes of transportation change. A41 refers to the route from Nakornluang Port to Mittraphap Road with truck as the mode of transportation. Lastly, A51 refers to the route from Mittraphap Road to Cement Plant Saraburi with truck as the mode of transportation.

Table 4.5: Possible multimodal transportation routes

Possible multimodal routes	Segmented routes									
	1	2	3	4	5	6	7	8	9	10
1	A11	A21	A31	A41	A51					
2	A12	A22	A32	A42	A52	A62				
3	A13	A23	A33	A43	A53	A63				
4	A14	A24	A34	A44	A54	A64	A74	A84	A94	A104
5	A15	A25	A35	A45	A55	A65	A75	A85	A95	
6	A16	A26	A36	A46	A56	A66				
7	A17	A27	A37	A47						
8	A18	A28	A38	A48	A58					

This study applies quantitative risk analysis to determine the value of decision variables for risk evaluation and to calculate the level of risk in certain activities [9]. Risk within traditional transportation is able to be calculated by multiplying the probability of accident occurrence by accident consequence as demonstrated in Equation (4.1) [9]:

$$R_{ij} = P_{ij} \times C_{ij} \tag{4.1}$$

where R_{ij} is risk level along route segment i of multimodal route j, P is the possibility of accident occurrence along route segment i of multimodal route j and C is the consequences of the accident along route segment i of multimodal route j.

There are many types of risk associated with multimodal transportation. The interviewed experts stated that the increasing risk trend is based on transportation mode and shipping distance. This has an implication for the quantitative risk analysis, as the longer the distances, the higher the level of risk. Since the estimation of the scores of risk is based on the consensus of contradicted opinions from the experts, an appropriate risk assessment model is created to calculate the weighted risk level according to shipping distance. The risk assessment within multimodal transportation is considered as MCDM problem with l criteria ($p = 1, .., l$) The ratio between the distance of each segmented route and the total distance of multimodal transportation route is presented as $\triangle E_{A_{ijpk}}$. In accordance with Equation (4.1), the quantitative risk assessment can be calculated as demonstrated in Equation (4.2).

$$R_{A_{ijpk}} = P_{A_{ijpk}} \times C_{A_{ijpk}} \times \triangle E_{A_{ijpk}} \tag{4.2}$$

where $R_{A_{ijpk}}$ is the risk level of segmented route i of multimodal route j for criteria p by expert k who assesses link A_{ij}. $P_{A_{ijpk}}$ is the probability assessment scale rank (1-5) of link A_{ij} for criteria p by expert k who assesses link A_{ij}. $C_{A_{ijpk}}$ is

Table 4.6: The rank of probability and severity assessment scale

Rank	Severity (C)					
	Probability (P)	Freight damaged risk *	Infrastructure risk *	Operational risk *	Security risk *	Environmental risk *
1	1%	$\leq$ 1%	$\leq$ 1%	$\leq$ 1%	$\leq$ 1%	$\leq$ 1%
2	$\leq$ 10%	1-5%	1-5%	1-5%	1-5%	1-5%
3	$\leq$ 20%	6-10%	6-10%	6-10%	6-10%	6-10%
4	20-50%	11-20%	11-20%	11-20%	11-20%	11-20%
5	$>$ 50%	>20%	>20%	>20%	>20%	>20%

increased cost and time of logistics *.

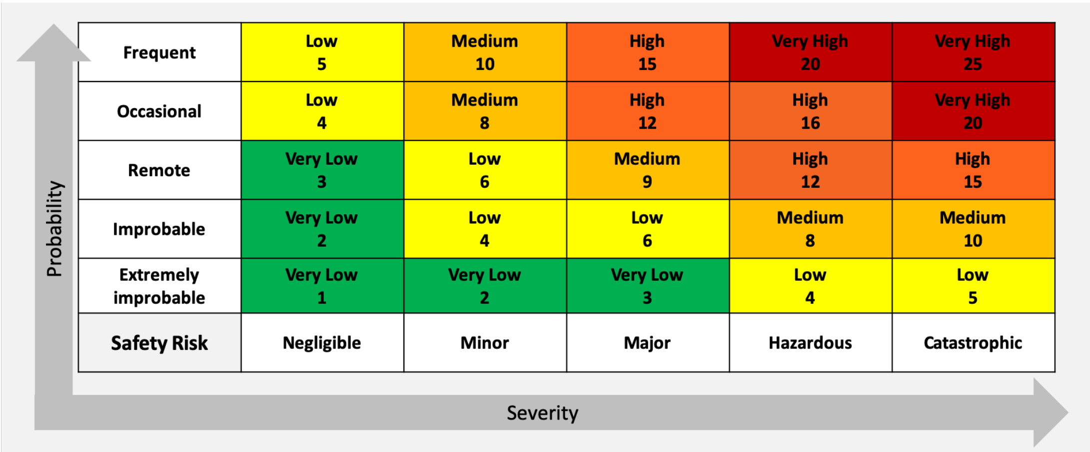


Figure 4.7: Risk matrix based on expert opinion

the severity impact assessment scale rank (1-5) of link A_{ij} for criteria p by expert k who assesses link A_{ij}. $\triangle E_{A_{ijpk}}$ is the ratio between distances of segmented route i and the total distance of multimodal route j for criteria p by expert k who assesses link A_{ij}.

Table 4.6 is the result which was developed using the information gained from previous studies and the opinions of 10 interviewed experts. It shows the ranking scale in probability assessment and severity impact assessment which are presented with the percentage of increased logistics cost and time spent on the route. Crucially, the decision-making environment requires that opinions of multiple experts are taken into account. Nevertheless, these experts might not have the same degree of experience and knowledge, so their opinions may not have equal degree of relevancy. Therefore, in order to facilitate the process of assessment, numerical scores (assessment grades) should be presented in linguistic terms (Very high, High, Medium, Low and Very low) when measuring the importance of different criteria [47]. Figure 4.7 demonstrates a risk matrix with the probability assessment scale rank (1-5) on the horizontal axis and the severity impact assessment scale rank (1–5) on the vertical axis.

Once the transportation risks were determined, the level of risks were then calculated as demonstrated in Equation (4.2). The risk matrix was converted into assessment scores in linguistic terms in order to quantitatively describe the risks associated with multimodal transportation as shown in Table 4.7.

Table 4.5 shows the process of calculating of the level of risk of the segmented route A_{11}. Concerning the freight damaged risk of this route, the first expert defines the probability rank as $P_{A_{1111}} = 3$ and the impact severity rank as $C_{A_{1111}} = 3$. The ratio between the distance of segmented route and the total distance of the route is $\triangle E_{A_{1111}} = \frac{195km}{207km} = 0.920$. Therefore, the level of risk level of A_{11} concerning the freight damaged risk this route is $3 \times 3 \times 0.920 = 8.280$. The risk score can be roughly measured as Medium as shown in Figure. 4.7. Experts 1–5 assess the risk as Medium, experts 6–9 assess it as Low, and the last one as Very Low. The remaining data are described in the same manner in Table 4.7.

Using FAHP to determine the weights of criteria

Based on literature review and the interviews with the experts, the previous section presents five categories of risk in the context of multimodal transportation, including risks associated with freight damage, infrastructure and equipment, operation, security, and environment. The Fuzzy AHP is utilized to analyze these risks and determine their importance weight. For risk analysis process, the criteria are determined by the experts who considered the pairwise judgment matrices. The relative important weights are assessed in linguistic term, before being converted into the TFNs using conversation scale demonstrated in Table 3.2. The pairwise judgment matrices are converted to a positive fuzzy number with the use of the standard TFNs.

In order to be certain that the pairwise matrix is consistent, the consistency in a crisp comparison matrix is assessed taking into account the criteria presented in the Fuzzy AHP section. A triangular fuzzy number of the pairwise comparison matrix of the risk categories is defuzzified to a crisp number. The result is that, the max of the fuzzy crisp matrix is 5.301. The dimension of matrix is 5; thus, the RI is 1.12 for $n = 5$. The calculation of the consistency index (CI) and the consistency ratio (CR) are demonstrated in Equations (3.19)–(3.20). The value of CI is 0.075 and CR is 0.070 ($< 10\%$). Therefore, it is acceptable and consistent to use the pairwise comparison matrix in the context of the multimodal risk factors. Then, the pairwise comparison fuzzy values are transformed into crisp values with the use of Chang's extent analysis as elaborated in Table 3.2. Equation (3.8)-(3.11) are used to calculate the fuzzy synthesis extent values and the priority weights.

Table 4.7: Risk assessment data

Segmented route	Assessment risk criteria																								
	Freight damaged					Infrastructure					Operational					Security					Environmental				
	VH	H	M	L	VL	VH	H	M	L	VL	VH	H	M	L	VL	VH	H	M	L	VL	VH	H	M	L	VL
A_{11}	0	0	5	4	1	0	0	0	10	0	0	2	5	3	0	0	2	6	1	1	0	0	5	3	2
A_{21}	0	0	5	5	0	0	0	0	0	10	0	0	5	5	0	1	2	3	2	2	4	6	0	0	0
A_{31}	0	0	2	3	5	3	4	1	1	1	1	1	4	2	2	0	0	10	0	0	0	4	6	0	0
A_{41}	0	0	0	0	10	0	4	4	1	1	1	5	4	0	0	1	1	8	0	0	2	2	4	1	1
A_{51}	0	0	5	5	0	0	0	0	0	10	0	4	6	0	0	0	1	9	0	0	2	2	6	0	0
A_{12}	2	3	3	1	1	1	2	7	0	0	1	6	3	0	0	5	2	1	1	1	10	0	0	0	0
A_{22}	0	0	0	5	5	0	1	5	2	2	1	1	8	0	0	0	0	10	0	0	0	10	0	0	0
A_{32}	0	0	10	0	0	2	2	2	2	2	0	0	2	4	4	0	2	3	5	0	0	3	7	0	0
A_{42}	1	2	4	2	1	2	4	4	0	0	0	1	9	0	0	0	0	2	4	4	0	4	3	2	1
A_{52}	0	0	0	10	0	3	2	2	2	1	0	0	0	0	10	1	1	2	3	3	0	5	5	0	0
A_{62}	2	5	2	1	0	2	1	5	1	1	0	1	1	4	4	0	0	0	3	7	0	10	0	0	0
A_{13}	0	0	3	7	0	2	1	2	2	3	0	2	8	0	0	0	1	5	4	0	0	10	0	0	0
A_{23}	0	2	2	6	0	0	2	3	5	0	0	1	9	0	0	0	0	10	0	0	0	10	0	0	0
A_{33}	0	0	10	0	0	0	3	4	3	3	0	0	10	0	0	0	0	10	0	0	0	2	4	4	0
A_{43}	0	0	0	5	5	0	0	5	5	0	0	0	10	0	0	0	1	9	0	0	2	1	3	2	2
A_{53}	0	0	3	7	0	0	2	3	5	0	0	0	4	6	0	0	0	10	0	0	0	2	3	0	5
A_{63}	0	0	1	9	0	0	0	2	8	0	0	0	3	7	0	0	0	5	5	0	2	1	5	1	1
A_{14}	0	0	0	0	10	0	0	0	4	6	0	0	0	8	2	0	0	6	4	0	0	2	8	0	0
A_{24}	2	1	7	0	0	0	0	10	0	0	0	1	5	4	0	0	0	4	6	0	0	1	9	0	0
A_{34}	1	1	5	2	1	1	2	3	2	2	0	1	8	1	0	0	0	10	0	0	2	3	3	1	1
A_{44}	1	2	1	3	3	0	1	9	0	0	0	3	7	0	0	0	2	3	5	0	0	3	6	0	1
A_{54}	2	2	2	2	2	0	1	7	2	0	0	0	10	0	0	2	2	2	2	2	0	2	2	3	3
A_{64}	0	4	1	3	2	0	1	8	1	0	0	0	10	0	0	0	0	0	0	10	0	3	7	0	0
A_{74}	1	1	1	4	3	0	1	9	0	0	0	0	9	1	0	2	0	4	4	0	0	0	10	0	0
A_{84}	0	2	5	3	0	0	0	10	0	0	2	6	2	0	0	0	2	8	0	0	0	0	5	5	0
A_{94}	2	1	5	2	0	0	0	10	0	0	0	0	10	0	0	0	1	4	5	0	0	0	0	5	5
A_{104}	0	0	2	4	4	0	1	8	1	0	0	0	0	5	5	1	2	3	2	2	0	1	4	5	0
A_{15}	1	1	6	1	1	0	1	9	0	0	0	6	2	2	0	0	3	2	5	0	0	2	6	2	0
A_{25}	0	0	7	3	0	0	0	10	0	0	0	0	10	0	0	2	4	2	1	1	2	3	3	1	1
A_{35}	1	1	8	0	0	1	1	3	3	2	0	2	8	0	0	1	2	4	2	1	1	1	5	2	1
A_{45}	1	2	5	2	0	1	2	4	2	1	0	3	4	3	0	0	1	5	4	0	2	2	6	0	0
A_{55}	3	2	5	0	0	0	0	8	2	0	0	1	9	0	0	0	3	6	1	0	0	1	9	0	0
A_{65}	1	2	4	3	0	0	0	0	5	5	0	1	5	2	2	0	2	3	5	0	1	1	8	0	0
A_{75}	1	1	4	2	2	0	0	6	4	0	1	1	3	4	1	0	0	10	0	0	0	1	9	0	0
A_{85}	0	0	5	5	0	1	1	2	6	0	2	1	5	1	1	0	0	10	0	0	0	0	10	0	0
A_{95}	2	1	7	0	0	0	0	7	3	0	2	2	4	1	1	0	0	5	5	0	0	0	10	0	0
A_{16}	0	0	5	5	0	2	2	4	1	1	0	0	0	10	0	0	0	0	5	5	0	0	0	10	0
A_{26}	2	1	4	3	0	3	2	3	2	0	0	0	0	0	10	0	0	7	3	0	0	0	10	0	0
A_{36}	0	3	4	3	0	0	0	3	7	0	5	5	0	0	0	0	1	8	1	0	0	0	10	0	0
A_{46}	2	2	6	0	0	1	1	6	1	1	0	5	5	0	0	2	2	4	1	1	0	1	9	0	0
A_{56}	2	0	7	1	0	0	1	9	0	0	0	0	10	0	0	1	1	3	3	2	1	1	8	0	0
A_{66}	0	1	8	1	0	0	0	10	0	0	0	4	3	3	0	2	2	5	1	0	2	2	5	1	0
A_{17}	0	0	5	5	0	0	2	8	0	0	1	1	8	0	0	2	3	3	1	1	0	10	0	0	0
A_{27}	0	3	4	3	0	3	5	2	0	0	4	6	0	0	0	2	4	2	2	0	2	2	4	1	1
A_{37}	2	2	3	2	1	0	0	5	5	0	0	8	2	0	0	0	4	4	2	0	0	0	10	0	0
A_{47}	1	2	6	0	1	0	5	5	0	0	0	3	5	2	0	0	2	5	3	0	0	0	0	0	10
A_{18}	0	0	4	3	3	0	0	10	0	0	0	0	10	0	0	0	0	2	2	6	0	8	2	0	0
A_{28}	5	5	0	0	0	5	5	0	0	0	2	8	0	0	0	0	0	3	7	0	1	1	5	2	1
A_{38}	0	0	5	5	0	4	6	0	0	0	3	5	2	0	0	0	0	0	2	8	2	1	6	1	0
A_{48}	0	0	10	0	0	1	2	5	1	1	0	10	0	0	0	0	2	6	2	0	3	5	1	1	0
A_{58}	0	0	6	4	0	1	3	3	2	1	0	0	8	2	0	0	0	7	3	0	0	1	9	0	0

Note: VH is very high, H is high, M is medium, L is low and VL is very low.

$$
\begin{aligned}
\sum_{j=1}^{5} M_{g_1}^{j} &= (1.00, 1.00, 1.00) + (1.74, 2.14, 2.49) \\
&\quad + (2.70, 3.38, 4.00) + (3.10, 4.21, 5.28) \\
&\quad + (2.70, 3.38, 4.00) = (11.25, 14.11, 16.77) \\
\sum_{i=1}^{5}\sum_{j=1}^{5} M_{g_i}^{j} &= (11.25, 14.11, 16.77) + (13.84, 16.98, 20.14) \\
&\quad + (6.20, 6.95, 7.69) + (3.11, 3.22, 3.40) \\
&\quad + (2.56, 2.66, 2.83) = (36.948, 43.926, 50.835)
\end{aligned}
$$

$$
\begin{aligned}
\left[\sum_{i=1}^{5}\sum_{j=1}^{5} M_{g_i}^{j}\right]^{-1} &= \left(\frac{1}{50.835}, \frac{1}{43.926}, \frac{1}{36.948}\right) \\
&= (0.020, 0.023, 0.027)
\end{aligned}
$$

After the weight vector is obtained in Equation (3.12), the normalized weight vector (N_i) is utilized in order to get criteria priority weight vector as demonstrated in Equations (3.14)–(3.17). Below is the smallest value of possibility for the pairwise comparisons.

$$
\begin{aligned}
d'(F) &= \min V(F \geq I, O, S, E) = 0.329 \\
d'(I) &= \min V(I \geq F, O, S, E) = 0.398 \\
d'(O) &= \min V(O \geq F, I, S, E) = 0.162 \\
d'(S) &= \min V(S \geq F, I, O, E) = 0.075 \\
d'(E) &= \min V(E \geq F, I, O, S) = 0.062
\end{aligned}
$$

As demonstrated, the weight vector is W_J = (0.329, 0.398, 0.162, 0.075, 0.062). The normalized preference weights for each risk are W = (0.321, 0.388, 0.157, 0.073, 0.061). These numbers represent the relative weight criteria of the risks associated with freight damage (0.321), infrastructure (0.388), operation (0.157), security (0.073), and environment (0.061) respectively (Table 4.8).

FAHP-DEA hybrid model

The FAHP-DEA hybrid model is used in MCDM problems to group a large number of alternatives into categories characterized by linguistic assessment grades [46]. In this study, 51 alternatives are concerned and grouped into 5 main criteria with their weights being evaluated with the use of the FAHP method in order to obtain the risk score of each segmented route.

Each of the five multimodal transportation risk criteria are evaluated with the use of assessment grades. For instance, the set of assessment grades for four of the criteria is $G = \{\text{Very high, High, Medium, Low, Very low}\} = \{\text{VH, H, M, L, VL}\}$. Different sets of assessment grades are determined based on the risk matrix.

The distribution decision matrix of the results of the assessment of the total of 51 segmented routes evaluated by 10 experts is demonstrated in Table 4.7. Concerning the risk of freight damage of the segmented route A_{11}, half of the experts rated it as medium, while the other four experts rated it as low and one as very low. This way of assessing the level of risk is the same for other routes. Afterwards, the risk assessment data are utilized to obtain the local risk scores of each criterion with the use of the DEA model as presented in Equation (3.3)-(3.5). Table 4.9 shows an example of the freight damaged risk assessment in order to achieve the best solutions a decision variable $S(L_{pk})$ which can be solved with the use of Equation (3.5). The weight of each decision variable is assigned to the output NE_{ijpk}. With the use of DEA model, the common weights can be demonstrated as follows:

$$
\begin{aligned}
&\text{Maximize} \quad \alpha \\
&\text{Subject to} \\
&0S(VH_{11}) + 0S(H_{11}) + 5S(M_{11}) + 4S(L_{11}) + 1S(VL_{11}) \leq 1 \\
&0S(VH_{11}) + 0S(H_{11}) + 5S(M_{11}) + 5S(L_{11}) + 0S(VL_{11}) \leq 1 \\
&0S(VH_{11}) + 0S(H_{11}) + 2S(M_{11}) + 3S(L_{11}) + 5S(VL_{11}) \leq 1 \\
&0S(VH_{11}) + 0S(H_{11}) + 0S(M_{11}) + 0S(L_{11}) + 10S(VL_{11}) \leq 1 \\
&0S(VH_{11}) + 0S(H_{11}) + 5S(M_{11}) + 5S(L_{11}) + 0S(VL_{11}) \leq 1 \\
&\vdots \\
&0S(VH_{11}) + 0S(H_{11}) + 6S(M_{11}) + 4S(L_{11}) + 0S(VL_{11}) \leq 1 \\
&S(VH_{11}) + 0S(H_{11}) + 0S(M_{11}) + 0S(L_{11}) + 0S(VL_{11}) \geq 2S(H_{11}) \\
&0S(VH_{11}) + 2S(H_{11}) + 0S(M_{11}) + 0S(L_{11}) + 0S(VL_{11}) \geq 3S(M_{11}) \\
&0S(VH_{11}) + 0S(H_{11}) + 3S(M_{11}) + 0S(L_{11}) + 0S(VL_{11}) \geq 4S(L_{11}) \\
&0S(VH_{11}) + 0S(H_{11}) + 0S(M_{11}) + 4S(L_{11}) + 0S(VL_{11}) \geq 5S(VL_{11}) \\
&S(VH_{11}), S(H_{11}), S(M_{11}), S(L_{11}), S(VL_{11}) \geq 0
\end{aligned}
\tag{4.3}
$$

where $s(VH)$ is the optimal scoring of the assessment grade Very high, $S(H)$ is the optimal scoring of the assessment grade High, $S(L)$ is the optimal scoring of the assessment grade Low and $S(VL)$is the optimal scoring of the assessment grade Very low and α is the optimal local weight of each criterion. Additionally, the optimal solutions of decision variables $S(L_{pk})$ for other criteria can be computed in a similar way.

Equation (3.5) is used in order to calculate the optimal solutions of each criterion. Concerning the risk associated with freight damage, infrastructure, equipment, and operation, the optimal solutions are as follows:

$s^*(VH) = 0.13333$, $s^*(H) = 0.066667$, $s^*(M) = 0.044444$, $s^*(L) = 0.033333$, $s^*(VL) = 0.026666$ and $\alpha^* = 0.999985$

Concerning the risk associated with security and environment respectively, the optimal solutions are as follows:

$s^*(VH) = 0.18462$, $s^*(H) = 0.092307$, $s^*(M) = 0.061537$, $s^*(L) = 0.046151$, $s^*(VL) = 0.036917$ and $\alpha^* = 0.867769$

$s^*(VH) = 0.14286$, $s^*(H) = 0.071428$, $s^*(M) = 0.047619$, $s^*(L) = 0.035714$, $s^*(VL) = 0.028571$ and $\alpha^* = 1.000008$

Table 4.9 shows the optimal solutions of each criterion S (Lpk). Then, the local risk scores of the 51 segmented routes in five criteria are obtained as shown in Equation (3.5) and with the results as shown in Table 4.10.

Then, the SAW method is used, and the local risk scores are aggregated into an overall risk score for each decision alternative as demonstrated in Equation (3.6). For instance, the local risk of the route A11 can calculated as follows:

Freight damaged risk: $[(5\times0.044444) + (4\times0.033333) + (1\times0.026666) = 0.382218$
Infrastructure risk:$10\times0.033333 = 0.333333$
Operational risk: $[(2\times0.066666) + (5\times0.044444) + (3\times0.033333) = 0.455551$
Security risk: $[(2\times0.092307) + (6\times0.061537) + (1\times0.046151) + (1\times0.036917) = 0.636904$
Environmental risk: $[(5\times0.047619) + (3\times0.035714) + (2\times0.028571) = 0.402379$

Table 4.9 demonstrates the overall risk scores which can be obtained from assessing the relative weight criteria from FAHP (Table 4.7) and from the use of the SAW method as seen in Equation (3.6). The total risk score regarding the segmented route A_{11} is:

$V(A_{11}) = (\mathrm{w}_1 v_{111}) + (w_2 v_{111}) + (w_3 v_{111}) + (w_4 v_{111}) + (w_5 v_{111}) = (0.321 * 0.382) + (0.388 * 0.333) + (0.157 * 0.455) + (0.073 * 0.061) = 0.394608$

Table 4.8: Fuzzy weight of risk factors and their categories

Categories	Importance weight	Ranking
Freight damaged risk (F)	0.321	2
Infrastructure risk (I)	0.388	1
Operational risk (O)	0.157	3
Security risk (S)	0.073	4
Environmental risk (E)	0.061	5

Table 4.9: The optimal solution of each criterion

Criteria	Optimal solutions					
	$s(VH)$	$s(H)$	$s(M)$	$s(L)$	$s(VL)$	α
Freight damaged risk	0.13333	0.066667	0.044444	0.033333	0.026666	0.999985
Infrastructure risk	0.13333	0.066667	0.044444	0.033333	0.026667	0.999985
Operational risk	0.13333	0.066666	0.044444	0.033333	0.026666	0.999985
Security risk	0.18462	0.092307	0.061537	0.046151	0.036917	0.867769
Environmental risk	0.14286	0.071428	0.047619	0.035714	0.028571	1.000008

Table 4.10 shows the risk scores of multimodal routes, and the ranking is shown in Table 4.11 with route 4 having the highest risk score of 4.747 and route 1 with the lowest risk score of 2.241. The optimal route is A-1-5-18-B with the modes of transportation being ship and truck.

This study aims at applying a decision support approach on the industrial sector with the focus on multimodal transportation risk practices. It contributes to the existing literature and knowledge on the aspects of risk identification, risk analysis, and risk prioritization at strategic level in business processes. Crucially, with the focus on coal industry companies, as risks can arise from many different activities, this necessitates great care when selecting which route is the best one to choose. The results show that route 1 is the one with the lowest risk score, following by route 7, route 3, route 8, route 2, route 6, route 5, and route 4, respectively. The higher the risk score, the greater managerial concern is needed. This demonstrates that the FAHP-DEA can be applied in multimodal transportation risk analysis which, in turn, can effectively facilitate the decision-making process of route selection.

Table 4.10: The overall multimodal transportation risk scores

Segmented route	The overall multimodal transportation risk scores					Overall risk scores
	Freight damaged (0.321)*	Infrastructure (0.388)*	Operational (0.157)*	Security (0.073)*	Environmental (0.060)*	
A_{11}	0.382218	0.333333	0.455551	0.636904	0.402379	0.394608
A_{21}	0.388885	0.266667	0.388885	0.719981	1.000008	0.402603
A_{31}	0.322217	0.771102	0.497777	0.615370	0.571426	0.560503
A_{41}	0.266666	0.504444	0.644436	0.769223	0.683337	0.480291
A_{51}	0.388885	0.266667	0.533328	0.646140	0.714290	0.402669
A_{12}	0.659992	0.577772	0.433329	1.000000	0.714280	0.620514
A_{22}	0.299995	0.408887	0.555548	0.615370	0.714280	0.430562
A_{32}	0.444444	0.608882	0.328884	0.599980	0.547617	0.507650
A_{42}	0.537772	0.711104	0.466662	0.455346	0.528568	0.587257
A_{52}	0.333333	0.715545	0.266660	0.649205	0.595235	0.510041
A_{62}	0.722216	0.615547	0.351106	0.396872	0.714280	0.598170
A_{13}	0.366663	0.568882	0.488884	0.769216	0.714280	0.514784
A_{23}	0.582216	0.566666	0.466662	0.615370	0.714280	0.568399
A_{33}	0.444444	0.557777	0.444444	0.615370	0.590472	0.509728
A_{43}	0.299995	0.388885	0.444444	0.646140	0.628575	0.402372
A_{53}	0.366663	0.566666	0.377774	0.615370	0.428568	0.467918
A_{63}	0.344441	0.355552	0.366663	0.538440	0.659528	0.385473
A_{14}	0.266666	0.293334	0.319996	0.553826	0.523808	0.321927
A_{24}	0.644435	0.444444	0.422218	0.523054	0.499999	0.514253
A_{34}	0.515549	0.519996	0.455551	0.615370	0.707146	0.526706
A_{44}	0.491105	0.466663	0.511106	0.599980	0.528569	0.494985
A_{54}	0.608888	0.444444	0.444444	0.843064	0.430949	0.525524
A_{64}	0.464443	0.455552	0.444444	0.369170	0.547617	0.455919
A_{74}	0.457771	0.466663	0.433329	0.799992	0.476190	0.483473
A_{84}	0.455553	0.444444	0.755544	0.676910	0.416665	0.512278
A_{94}	0.622213	0.444444	0.444444	0.569210	0.321425	0.503185
A_{104}	0.328884	0.455552	0.299995	0.719981	0.440474	0.408788
A_{15}	0.526666	0.466663	0.555555	0.630750	0.499998	0.513916
A_{25}	0.411107	0.444444	0.444444	0.944610	0.707146	0.486146
A_{35}	0.555549	0.486662	0.488884	0.744601	0.552382	0.531937
A_{45}	0.555555	0.537773	0.477773	0.584596	0.714290	0.548130
A_{55}	0.755544	0.422218	0.466662	0.692294	0.499999	0.560657
A_{65}	0.544439	0.300000	0.408884	0.599980	0.595240	0.435382
A_{75}	0.497771	0.399996	0.493326	0.615370	0.499999	0.467855
A_{85}	0.388885	0.488883	0.615545	0.615370	0.476190	0.485185
A_{95}	0.644435	0.411107	0.637767	0.538440	0.476190	0.534937
A_{16}	0.388885	0.637777	0.444444	0.538440	0.476190	0.510400
A_{26}	0.611102	0.733322	0.266666	0.569212	0.476190	0.593080
A_{36}	0.477776	0.366663	0.999988	0.630754	0.476190	0.527947
A_{46}	0.666658	0.526661	0.555555	0.883070	0.499999	0.600566
A_{56}	0.611101	0.466663	0.444444	0.673825	0.595240	0.532441
A_{66}	0.455552	0.444444	0.499995	0.907690	0.702385	0.506178
A_{17}	0.388885	0.488886	0.555548	0.913840	0.714280	0.511933
A_{27}	0.477776	0.822213	0.933316	0.953844	0.683337	0.730328
A_{37}	0.626658	0.388885	0.622216	0.707678	0.476190	0.530515
A_{47}	0.559994	0.555555	0.488884	0.630752	0.285710	0.535653
A_{18}	0.357773	0.444444	0.444444	0.436878	0.666662	0.429504
A_{28}	0.999985	0.999985	0.799988	0.507668	0.552382	0.905481
A_{38}	0.388885	0.933322	0.822208	0.387638	0.678576	0.685781
A_{48}	0.444444	0.548884	0.666666	0.646138	0.869053	0.560359
A_{58}	0.399996	0.586663	0.422218	0.569212	0.499999	0.494326

Relative weights from FAHP *.

Table 4.11: Overall risk scores

Route	Freight Damaged	Infrastructure	Operational	Security	Environmental	Total risk scores
1	0.561	0.831	0.397	0.247	0.204	2.241
2	0.962	1.411	0.378	0.271	0.231	3.254
3	0.772	1.166	0.408	0.277	0.226	2.849
4	1.559	1.721	0.713	0.458	0.296	4.747
5	1.567	1.536	0.722	0.436	0.304	4.564
6	1.031	1.232	0.506	0.307	0.195	3.271
7	0.659	0.875	0.409	0.234	0.131	2.308
8	0.832	1.363	0.497	0.186	0.198	3.075

4.4 Using FAHP to determine the weight of criteria

With the use of FAHP, the weights of criteria based on the opinions of the experts are determined. These weights are then integrated in the objective function of ZOGP. In this study, the coal multimodal transportation in Thailand is the case study which tests the methodology proposed. Below are the steps of FAHP analysis which were performed in this study.

4.4.1 Identifying hierarchical structure of factors

The first step of FAHP is identifying transportation factors. Based on Chang's extend analysis and the opinions of the experts, 8 decision criteria are determined including transportation time, cost, risk, and other five sub-criteria. With the use of Fuzzy AHP methodology, the risk factors are categorized into 8 main categories and demonstrated in Figure 4.8.

4.4.2 Testing the coherence of the pairwise matrix

Within the decision-making environment, different opinions of the experts have to be taken into consideration. Nevertheless, different experts may not have the same degree of knowledge and experience. Therefore, differences in weights or importance must be looked at. In this study, five highly-qualified experts within the field of multimodal transportation were interviewed, and the judgment matrix is developed for the identity profiles of each expert.

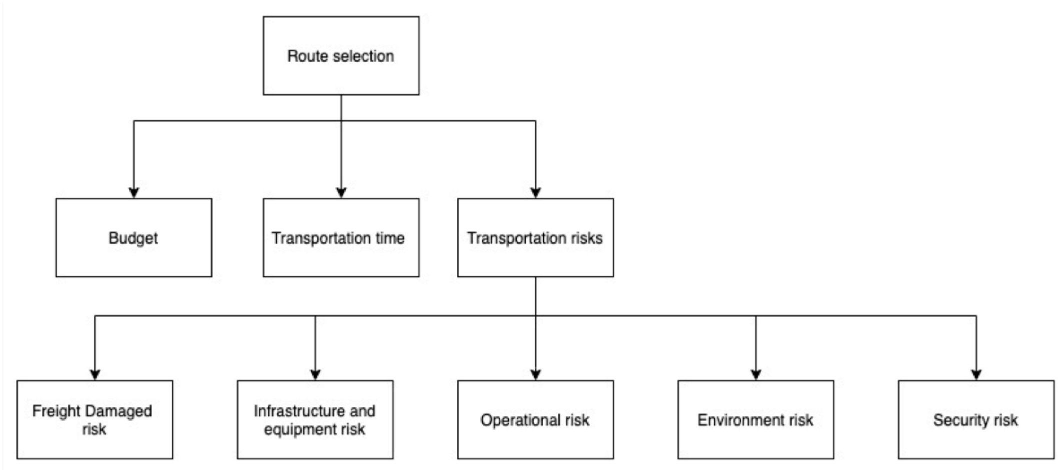


Figure 4.8: A graphical hierarchy model

The results demonstrate that the highest eigenvalue of the judgment matrix is 3.159, with the consistency ratio being 0.0265 (< 0.1). Thus, the judgment matrix adheres to the standard consistency requirement. Then, the weighted average score of each expert is normalized to obtain the priority weights of each expert.

4.4.3 Calculating the weight of each criterion

To calculate the weights of all criteria regarding the multimodal transportation process, the pairs-wise judgment matrices are considered by the experts who evaluate their relative importance with the use of linguistic evaluations which are then converted into TFNs based on conversation scale demonstrated in Table 3.2. Based on the opinions of the experts, pair-wise judgment matrices are then converted into positive fuzzy values with the use of the standard TFNs. Table 4.12-4.13 demonstrate the constructed fuzzy pair-wise judgment matrices with the categories of main transportation criteria being cost, time, and risk (C, T, R) and the sub-criteria being freight damaged risk, infrastructure risk, operational risk, security risk, and environmental risk (R1, R2, R3, R4, R5).

Then, the experts were asked to make pairwise comparisons of these criteria using linguistic terms as demonstrated in Table 3.2. Tables 4.14–4.15 show the pairwise comparison matrix of all criteria derived from the calculation of the geometric mean of preferences values.

Equation (3.8) show the calculation of the category weights of all factors in different categories. The extent values of criteria (C, T, R) were and their priority weights were calculated as demonstrated in Equations (3.9)-(3.14). An example of

Table 4.12: Pairwise comparison matrix of the transport cost, time and risk

	C	T	R
C	(1.000,1.000,1.000)	(2.000,3.000,4.000)	(1.000,2.000,3.000)
T	(0.250,0.333,0.500)	(1.000,1.000,1.000)	(1.000,1.000,1.000))
R	(0.333,0.500,1.000)	(1.000,1.000,1.000)	(1.000,1.000,1.000)

Table 4.13: Geometric mean of the transport cost, time and risk

	C	T	R
C	(1.000,1.000,1.000)	(1.320,1.783,2.169)	(1.741,2.766,3.776)
T	(0.461,0.561,0.758)	(1.000,1.000,1.000)	(1.149,1.431,1.644))
R	(0.265,0.361,0.574)	(0.608,0.699,0.871)	(1.000,1.000,1.000)

the calculation of a priority weight is shown in Table 4.16. To sum up, the weight vector is W' = (0.550,0.294,0.209). After this value is normalized, the importance of attributes is W = (0.523, 0.279, 0.198). The results show that the most significant success factor is the transportation cost (C) with the highest weight among all the criteria.

4.4.4 Calculating the local weight for each sub-criteria weight

Table 4.16 shows the local weight and global weight of each factor, with the latter being determined by the multiplication of the local weight with the weight of its category within the hierarchical structure. The significance and prioritization of each factor is shown in the global fuzzy AHP weight. The local weight of each factor shows its significance within its respective category. For instance, the local weights of R1, R2, R3, R4 and R5 are 0.321, 0.388, 0.157, 0.073, and 0.061, respectively, with R2 (Infrastructure and equipment risk) having the highest value. R2 has its global weight of 0.077, being the highest rank global factor, while R5 (Environmental risk)

Table 4.14: Pairwise comparison matrix of the transport risks

	R1	R2	R3	R4	R5
R1	(1.000,1.000,1.000)	(4.000,5.000,6.000)	(2.000,3.000,4.000)	(2.000,3.000,4.000)	(2.000,3.000,4.000)
R2	(0.167,0.200,0.250)	(1.000,1.000,1.000)	(4.000,5.000,6.000)	(4.000,5.000,6.000)	(4.000,5.000,6.000)
R3	(0.250,0.333,0.500)	(0.167,0.200,0.250)	(1.000,1.000,1.000)	(6.000,7.000,8.000)	(6.000,7.000,8.000)
R4	(0.250,0.333,0.500)	(0.167,0.200,0.250)	(0.125,0.143,0.167)	(1.000,1.000,1.000)	(1.000,1.000,1.000)
R5	(0.250,0.333,0.500)	(0.167,0.200,0.250)	(0.125,0.143,0.167)	(1.000,1.000,1.000)	(1.000,1.000,1.000)

Table 4.15: Geometric mean of the transport risks

	R1	R2	R3	R4	R5
R1	(1.000,1.000,1.000)	(1.741,2.141 2.491)	(2.702,3.380,4.000)	(3.104,4.210,5.28)	(2.702,3.380,4.000)
R2	(0.402,0.467,0.574)	(1.000,1.000,1.000)	(4.704,5.720,6.732)	(4.704,5.720,6.732)	(3.031,4.076,5.102)
R3	(0.250,0.296,0.370)	(0.149,0.175 0.213)	(1.000,1.000,1.000)	(3.336,4.004, 4.590)	(1.431,1.476,1.516)
R4	(0.250,0.296,0.370)	(0.196,0.245, 0.330)	(0.660,0.678,0.699)	(1.000,1.000,1.000)	(1.000,1.000,1.000)
R5	(0.189,0.237,0.322)	(0.149,0.175,0.213)	(0.218,0.250,0.297)	(1.000,1.000,1.000)	(1.000,1.000,1.000)

Table 4.16: Fuzzy local and global weight of factors

Category	Category Weight	Sub-factor	Local weight	Local rank	Global weight	Global rank
Cost	0.523					1
Time	0.279					2
Risk	0.198	R1	0.321	2	0.064	4
		R2	0.388	1	0.077	3
		R3	0.157	3	0.031	5
		R4	0.073	5	0.014	6
		R5	0.061	4	0.012	7

has the lowest global weight, being the least significant factor among all the given sub-criteria risk factors.

4.4.5 Using FAHP to rank the factors

Table 4.16 shows the ranking of the success factors calculated by taking into account their global weight, with R2 (infrastructure and equipment risk) being the most significant sub-factor with the highest global weight. Concerning the opinions of the majority of the experts, the transportation cost (C) is the most significant factor with the weight of 0.523. These highly ranked factors should be taken into account by practitioners in order to improve their logistics activities.

4.4.6 Comparing with other approaches of decision-making

The results from FAHP-DEA model must be compared with that of the other fuzzy multi-criteria decision-making approaches (MCDM) which help determine the weights of criteria in order to ensure the coherence and validity of the model. This study also looked at the fuzzy best-worst method (FBWM) and fuzzy full consistency method (FFUCOM) which were utilized as input data as seen in Table 4.17 which demonstrates the DEA model. since the validity of MCDM method is based

Table 4.17: Alternative risk criteria weight ranks

Methods		Risk factors				
		F	I	O	S	E
FAHP	w_j	0.321	0.388	0.157	0.073	0.061
	Rank	2	1	3	4	5
FBWM	w_j	0.290	0.424	0.116	0.120	0.050
	Rank	2	1	4	3	5
FFUCOM	w_j	0.322	0.401	0.120	0.113	0.044
	Rank	2	1	3	4	5

on the pairwise comparison and the degree of consistency, both of which are the vital basis of FAHP method and DEA method.

In the previous section, the DEA, FAHP-DEA, FBWM-DEA, and FFUCOM-DEA models were analyzed and applied with the final results presenting the risk factor priority and the route ranking (Table 4.18).

The ranking demonstrates that route 4 has the highest weight compared to other risk factors, with the same ranking results shown in the FAHP-DEA and FFUCOM-DEA models, but with different results in the DEA and FBWM-DEA models. The weights in Table 4.17 are different because of the reasons given below.

- When the weight coefficients of the FAHP, FBWM, and FFUCOM models are determined (Table 4.16), the last model (FFUCOM) merely requires $n-1$ pairwise comparisons, the second model (FBWM) requires $2n-3$ pairwise comparisons, while the first model (FAHP) requires $n(n-1)/2$ pairwise comparisons.
- As the pairwise matrixes are compared, any scale (integer or decimal) can be applied in the FFUCOM, while only integer values can be used in the FBWM, and only a ratio scale can be used in the FAHP.
- While the FBWM model and the FAHP model are based on compliance with mathematical transitivity, the FFUCOM makes it possible to have a consistent model while at the same time achieving the conditions of transitivity.

4.4.7 Using Spearman's rank correlation coefficient and Pearson correlation coefficient to validate results

The correlation analysis can be used to depict the correlations between two variables which range from +1 to –1. A zero correlation means there is no connection between

Table 4.18: The results obtained using different methods

Methods		Routes							
		1	2	3	4	5	6	7	8
DEA	Risk scores	13.170	16.569	15.533	24.985	24.414	17.027	12.275	15.074
	Risk priority ranking	7	4	5	1	2	3	8	6
FAHP-DEA	Risk scores	2.241	3.254	2.849	4.747	4.564	3.271	2.308	3.075
	Risk priority ranking	8	4	6	1	2	3	7	5
FBWM-DEA	Risk scores	2.283	3.327	2.914	4.811	4.592	3.316	2.346	3.076
	Risk priority ranking	8	3	6	1	2	4	7	5
FFUCOM-DEA	Risk scores	2.256	3.300	2.883	4.809	4.604	3.309	2.335	3.053
	Risk priority ranking	8	4	6	1	2	3	7	5

the variables. A correlation of −1 means a perfect negative correlation (as one variable rises, the other falls), while a correlation of +1 means a perfect positive correlation (two variables go in similar direction).

Table 4.18 demonstrates that risk scores and risk priority ranking which present the connections of the results attained from fuzzy MCDM methods, with the use of Spearman's rank correlation coefficient to see the ranked values of variables and Pearson correlation coefficient to obtain the final scores as seen in Equations (4.4)-(4.5).

1. Spearman's rank correlation coefficient:

$$\text{Correlation} = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2-1)} \tag{4.4}$$

   where d_i is the difference between two rankings and n is the number of observations.

2. Pearson correlation coefficient:

$$\text{Correlation} = \frac{n\sum_{i=1}^{n} x_i y_i - \sum_{i=1}^{n} x_i \sum_{i=1}^{n} y_i}{\sqrt{n\sum_{i=1}^{n} x_i^2 - (\sum_{i=1}^{n} x_i)^2}\sqrt{n\sum_{i=1}^{n} y_i^2 - (\sum_{i=1}^{n} y_i)^2}} \tag{4.5}$$

   where n is the total number of values, x is the value in the first set of data, and y is the value in the second set of data.

Figure 4.9 demonstrates the results obtained from the use of Spearman's rank correlation coefficient and Pearson correlation coefficient, which validate the FAHP-DEA method, showing that the DEA method is less correlated with the final ranking while the FAHP-DEA is more correlated with the final ranking.

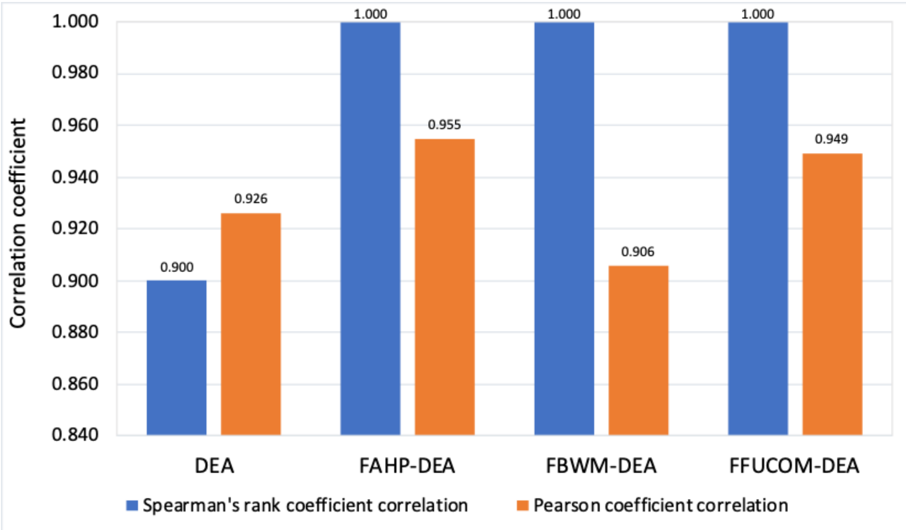


Figure 4.9: Correlation between the results of the risk priority ranking

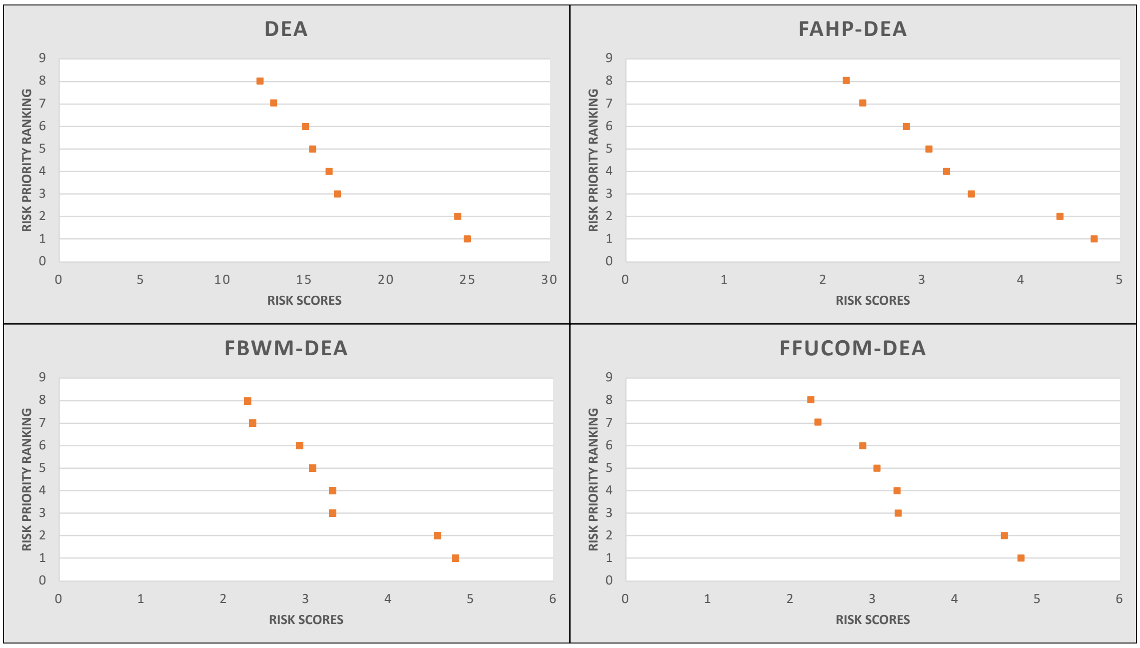


Figure 4.10: Scatter plots between the results of the risk scores and risk priority ranking.

Moreover, unlike other models, Table 4.17 shows that there is much less validation in the risk scores when using the FAHP-DEA method than when using the FFUCOM-DEA and other methods. The FAHP-DEA method makes it clear that the priority of risk factors remains stable, while the FFUCOM-DEA method shows that route 2 has the risk score of 3.300, and route 6 has the risk score of 3.309, suggesting that FFUCOM-DEA method generates nearly identical risk scores that are not easy to rank the risk priorities. Figure 4.10 shows the scatter plots which demonstrate how the FAHP-DEA method produces the adjacent risk scores that are more uniformly distributed than the scores generated with the use of other methods.

To conclude, the case study demonstrates that the best results can be obtained from the use of FAHP-DEA method compared to other methods. As a result, this study proposes that this method should be used in the selection of the optimal multimodal transportation routes. The FAHP method helps determine the weights of the risk criteria, while the DEA method helps determine the values of the linguistic terms when assessing the risks of all criteria. Then, the SAW method is used generate the overall risk score. Previous studies show that the FAHP-DEA method is suitable and effective for any complex MCDM problems, providing the comprehensive results of risk scores with priority ranking.

4.5 Using the ZOGP method to optimize the multimodal transportation routes selection

4.5.1 Data collection

The data concerning the cost and time of transportation of each route is collected from the experts by means of interviews. These data are then analyzed using the risk analysis (FAHP-DEA method) which involves the experts assessing the levels of risks within the multimodal transportation. The scores of transportation cost, time, and risk are demonstrated in Table 4.19.

4.5.2 Determining the significance weights

The last step is to use the ZOGP method in order to select the best route. Due to the binary nature of the selection variables and the conflicting criteria, the ZOGP method is suitable and easy to use in the route election process. The research by Kengpol et al. [8] provides a good example of the integration of the FAHP with the ZOGP. From the previous section, the FAHP method was used to obtain the

Table 4.19: Database of transportation routes

Route	Time (hrs.)	Cost (dollars)	Freight Damaged	Infrastructure	Operational	Security	Environmental
1	73	120.26	0.561	0.831	0.397	0.247	0.204
2	75	121.70	0.962	1.411	0.378	0.271	0.231
3	73	125.93	0.772	1.166	0.408	0.277	0.226
4	168	113.50	1.559	1.721	0.713	0.458	0.296
5	140	115.15	1.567	1.536	0.722	0.436	0.304
6	75	117.86	1.031	1.232	0.506	0.307	0.195
7	85	120.10	0.659	0.875	0.409	0.234	0.131
8	80	118.50	0.832	1.363	0.497	0.186	0.198

significance weights, with the application of the limitations and parameters to the ZOGP's objective function.

ILOG CPLEX Optimization is used in this case study. The deviation variables, decision variables, and parameters are demonstrated in Equations (3.21)–(3.30), and in Equations (3.31)–(3.34), the only one route is the best one for each situation. Given the limitations of each criteria, with the constraints including the budget which has to be lower than 150 USD, the lead time lower than 144 hours, the risk score below 10, the weights of the criteria (FAHP method) for the cost of transportation = 0.523, the time of transportation = 0.279, and the risk of transportation = 0.198. Concerning the weights of the sub-criteria, the weights of the freight damaged risk =0.321, the risk of infrastructure and equipment = 0.388, the operational risk = 0.157, the security risk = 0.073, and the environmental risk = 0.061, with CR below 0.1. Below demonstrates the integration of the FAHP method and the ZOGP method.

Objective function:

$$\text{Minimize} \quad Z_i = 0.523(\mathrm{d}_c^+) + 0.279(d_t^+) + 0.198(d_z^+(z'))$$

Subject to:

Transportation cost;

$$19.827\mathrm{x}_1 + 18.867x_2 + 16.047x_3 + 24.333x_4 + 23.333x_5 + 21.427x_6 + 19.333x_7 + 21.000x_8 - d_c^+ \leq 24.333$$

Transportation time;

$$50.694\mathrm{x}_1 + 52.083x_2 + 50.694x_3 + 116.667x_4 + 97.222x_5 + 52.083x_6 + 59.028x_7 + 55.556x_8 - d_t^+ \leq 100$$

The deviation of standard of risk scores;

$77.593\text{x}_1 + 67.458x_2 + 71.513x_3 + 52.530x_4 + 54.359x_5 + 67.294x_6 + 76.916x_7 + 69.246x_8 - d_z^+(z') \leq 77.593$

$$\text{z'}_i = \quad 0.321(d_{r1}^-) + 0.388(d_{r2}^-) + 0.157(d_{r3}^-) + 0.073(d_{r4}^-) + 0.061(d_{r5}^-)$$

Subject to:

Freight damaged risk;

$71.925\text{x}_1 + 51.877x_2 + 61.401x_3 + 22.054x_4 + 21.661x_5 + 48.452x_6 + 67.038x_7 + 58.405x_8 - (d_{r1}^-) \leq 71.925$

Infrastructure and equipment risk;

$58.440\text{x}_1 + 29.426x_2 + 41.713x_3 + 13.949x_4 + 23.218x_5 + 38.394x_6 + 56.242x_7 + 31.841x_8 - (d_{r2}^-) \leq 58.440$

Operational risk;

$80.164\text{x}_1 + 81.091x_2 + 79.622x_3 + 64.334x_4 + 63.879x_5 + 74.724x_6 + 79.534x_7 + 75.161x_8 - (d_{r3}^-) \leq 81.091$

Security risk;

$87.633\text{x}_1 + 86.432x_2 + 86.128x_3 + 77.109x_4 + 78.221x_5 + 84.657x_6 + 88.296x_7 + 90.700x_8 - (d_{r4}^-) \leq 80.296$

Environmental risk;

$89.804\text{x}_1 + 88.465x_2 + 88.702x_3 + 85.203x_4 + 84.814x_5 + 90.243x_6 + 93.469x_7 + 90.121x_8 - (d_{r5}^-) \leq 90.121$

$$x_1 + x_2 + ... + x_n = 1$$
$$d_c^+, d_t^+, d_z^+(z'), d_{r1}^-, d_{r2}^-, d_{r3}^-, d_{r4}^-, d_{r5}^- \geq 0$$

$$x_i = \text{ 0 or 1}; i = 1, 2, ..., n$$

Where
Z_i = The total deviation of objective or main decision criteria for i^{th} route
x_i = The zero-one variables representing the non-selection (zero) or selection (one) of route i = 1, 2, 3,..., n, subject to criteria right hand side (cost, time and risks)
d_c^+ = The overachievement deviation of cost.
d_t^+ = The overachievement deviation of time

$d_z^+(z'))$ = The overachievement deviation of risks
d_{r1}^- = Under achievements deviation of risk scores for freight damaged risk
d_{r2}^- = Under achievements deviation of risk scores for infrastructure and equipment risk
d_{r3}^- = Under achievements deviation of risk scores for operational risk
d_{r4}^- = Under achievements deviation of risk scores for security risk
d_{r5}^- = Under achievements deviation of risk scores for environmental risk

The ZOGP optimization model is used in this study in order to achieve specific goals, which can be achieved by ensuring that the cost and time of transportation, and all the risks associated with multimodal transportation should not exceed the user's acceptable limits. The deviation variables (d_j^+) refer to each goal's over-achievement percentage vectors , while w_j refer to the significance weights of the criteria. The results show that, transportation cost (w_c) = 0.523, (transportation time) (w_t) = 0.279, freight damage risk (w_{r1}) = 0.321, infrastructure and equipment risk (w_{r2}) = 0.388, operational risk (w_{r3}) = 0.157, security risk (w_{r4}) = 0.073, environmental risk (w_{r5}) = 0.061. X_i refers to the zero-one variables of route $i = 1, 2, ..., n$, under the constraint of budget, time, and risk. Ultimately, for each situation, there is only one route that is the optimal one.

This FAHP-ZOGP model is calculated with the use of ILOG CPLEX optimization software (Appendix C), with the results showing that Route 1 which involves the ship and truck transportation modes is the best route from Srichang to Saraburi Cement Industry, costing 120.26 USD and using the total of 73 hours, with the freight damage risk = 0.561, the infrastructure and equipment damage risk = 0.831, the operational risk = 0.397, the security risk = 0.247, and the environmental risk = 0.204. The stability of the algorithm has also been tested through the determination of the new relative weights of the key decision criteria. Instead of the first route, the best route could be the second one due to its lowest cost. The seventh route would be the best route if the importance is given to the deviation of standard risk score.

4.6 Post-evaluation and comparative study

The author also compared the results from FAHP-ZOGP with that of AHP-ZOGP, FBWM- ZOGP, and FFUCOM-ZOGP, and conducted the sensitivity analysis (simulation analysis or what-if analysis) on the weights of all the factors in order to ensure validity, robustness, and stability of the proposed model. All the methods above were used to calculate the priority of each factor which is compared with the results from the FAHP-ZOGP model. Table 4.20 demonstrates that the results concerning the prioritization of factors are similar in all four models. The impact of independent parameters on dependent parameters on the outcome were also ob-

Table 4.20: Comparison of criteria weight of FAHP-ZOGP and other methods

Methods	Cost	Time	Freight Damaged	Infrastructure	Operational	Security	Environmental
AHP-ZOGP	0.549*	0.171	0.069	0.074	0.055	0.046	0.035
	(1)**	(2)	(4)	(3)	(5)	(6)	(7)
FAHP-ZOGP	0.523	0.279	0.064	0.077	0.031	0.014	0.012
	(1)	(2)	(4)	(3)	(5)	(6)	(7)
FBWM-ZOGP	0.554	0.238	0.061	0.072	0.032	0.022	0.021
	(1)	(2)	(4)	(3)	(5)	(6)	(7)
FFUCOM-ZOGP	0.438	0.250	0.071	0.085	0.063	0.058	0.035
	(1)	(2)	(4)	(3)	(5)	(6)	(7)

*Weight of factor, ** Priority of factor

served. The output is considered sensitive if it varies significantly when changing the input variable from the lowest one to the highest one over a range, and the output is considered insensitive or robust if it does not change much. As most decisions are made under uncertainty, sensitivity analysis can help understand the uncertainties, advantages and disadvantages of a decision model. A conclusion can be reached by carrying out sensitivity analysis after replacing the uncertain parameters with expected values.

In this research, the sensitivity analysis can be conducted by altering the risk factor (the factor with the highest weight) in terms of cost, time, and infrastructure in order to see the overall impact when one factor is changed. For instance, Table 4.21-4.24 show a sensitivity analysis with the values of a group of factors decreasing and increasing by 10 %, 15% and 20% leading to the modification of other factors. From the result, the sensitivity analysis demonstrates that route 1 in the FAHP-ZOGP model has stable results even when the factors decrease or increase by +/-20%, indicating that the proposed model is robust and suitable for the decision-making process.

Table 4.21: +/- 5 % sensitivity analysis result

Factors	Methods	Cases	Results
Cost	AHP-ZOGP	Decreased by 5 %	Route 1
	AHP-ZOGP	Increased by 5 %	Route 2
	FAHP-ZOGP	Decreased by 5 %	Route 1
	FAHP-ZOGP	Increased by 5 %	Route 1
	FBWM-ZOGP	Decreased by 5 %	Route 2
	FBWM-ZOGP	Increased by 5 %	Route 2
	FFUCOM-ZOGP	Decreased by 5 %	Route 1
	FFUCOM-ZOGP	Increased by 5 %	Route 1
Time	AHP-ZOGP	Decreased by 5 %	Route 1
	AHP-ZOGP	Increased by 5 %	Route 1
	FAHP-ZOGP	Decreased by 5 %	Route 1
	FAHP-ZOGP	Increased by 5 %	Route 1
	FBWM-ZOGP	Decreased by 5 %	Route 1
	FBWM-ZOGP	Increased by 5 %	Route 1
	FFUCOM-ZOGP	Decreased by 5 %	Route 1
	FFUCOM-ZOGP	Increased by 5 %	Route 1
Infrastructure risk	AHP-ZOGP	Decreased by 5 %	Route 2
	AHP-ZOGP	Increased by 5 %	Route 2
	FAHP-ZOGP	Decreased by 5 %	Route 1
	FAHP-ZOGP	Increased by 5 %	Route 1
	FBWM-ZOGP	Decreased by 5 %	Route 1
	FBWM-ZOGP	Increased by 5 %	Route 1
	FFUCOM-ZOGP	Decreased by 5 %	Route 1
	FFUCOM-ZOGP	Increased by 5 %	Route 1

Table 4.22: +/- 10 % sensitivity analysis result

Factors	Methods	Cases	Results
Cost	AHP-ZOGP	Decreased by 10 %	Route 2
	AHP-ZOGP	Increased by 10 %	Route 2
	FAHP-ZOGP	Decreased by 10 %	Route 1
	FAHP-ZOGP	Increased by 10 %	Route 1
	FBWM-ZOGP	Decreased by 10 %	Route 2
	FBWM-ZOGP	Increased by 10 %	Route 3
	FFUCOM-ZOGP	Decreased by 10 %	Route 4
	FFUCOM-ZOGP	Increased by 10 %	Route 2
Time	AHP-ZOGP	Decreased by 10 %	Route 3
	AHP-ZOGP	Increased by 10 %	Route 3
	FAHP-ZOGP	Decreased by 10 %	Route 1
	FAHP-ZOGP	Increased by 10 %	Route 1
	FBWM-ZOGP	Decreased by 10 %	Route 3
	FBWM-ZOGP	Increased by 10 %	Route 2
	FFUCOM-ZOGP	Decreased by 10 %	Route 1
	FFUCOM-ZOGP	Increased by 10 %	Route 1
Infrastructure risk	AHP-ZOGP	Decreased by 10 %	Route 3
	AHP-ZOGP	Increased by 10 %	Route 2
	FAHP-ZOGP	Decreased by 10 %	Route 1
	FAHP-ZOGP	Increased by 10 %	Route 1
	FBWM-ZOGP	Decreased by 10 %	Route 2
	FBWM-ZOGP	Increased by 10 %	Route 3
	FFUCOM-ZOGP	Decreased by 10 %	Route 3
	FFUCOM-ZOGP	Increased by 10 %	Route 3

Table 4.23: +/- 15 % sensitivity analysis result

Factors	Methods	Cases	Results
Cost	AHP-ZOGP	Decreased by 15 %	Route 1
	AHP-ZOGP	Increased by 15 %	Route 2
	FAHP-ZOGP	Decreased by 15 %	Route 1
	FAHP-ZOGP	Increased by 15 %	Route 1
	FBWM-ZOGP	Decreased by 15 %	Route 4
	FBWM-ZOGP	Increased by 15 %	Route 4
	FFUCOM-ZOGP	Decreased by 15 %	Route 3
	FFUCOM-ZOGP	Increased by 15 %	Route 2
Time	AHP-ZOGP	Decreased by 15 %	Route 4
	AHP-ZOGP	Increased by 15 %	Route 5
	FAHP-ZOGP	Decreased by 15 %	Route 1
	FAHP-ZOGP	Increased by 15 %	Route 1
	FBWM-ZOGP	Decreased by 15 %	Route 6
	FBWM-ZOGP	Increased by 15 %	Route 5
	FFUCOM-ZOGP	Decreased by 15 %	Route 2
	FFUCOM-ZOGP	Increased by 15 %	Route 2
Infrastructure risk	AHP-ZOGP	Decreased by 15 %	Route 5
	AHP-ZOGP	Increased by 15 %	Route 5
	FAHP-ZOGP	Decreased by 15 %	Route 1
	FAHP-ZOGP	Increased by 15 %	Route 1
	FBWM-ZOGP	Decreased by 15 %	Route 4
	FBWM-ZOGP	Increased by 15 %	Route 3
	FFUCOM-ZOGP	Decreased by 15 %	Route 6
	FFUCOM-ZOGP	Increased by 15 %	Route 6

Table 4.24: +/- 20 % sensitivity analysis result

Factors	Methods	Cases	Results
Cost	AHP-ZOGP	Decreased by 20 %	Route 2
	AHP-ZOGP	Increased by 20 %	Route 2
	FAHP-ZOGP	Decreased by 20 %	Route 1
	FAHP-ZOGP	Increased by 20 %	Route 1
	FBWM-ZOGP	Decreased by 20 %	Route 3
	FBWM-ZOGP	Increased by 20 %	Route 3
	FFUCOM-ZOGP	Decreased by 20 %	Route 4
	FFUCOM-ZOGP	Increased by 20 %	Route 2
Time	AHP-ZOGP	Decreased by 20 %	Route 2
	AHP-ZOGP	Increased by 20 %	Route 2
	FAHP-ZOGP	Decreased by 20 %	Route 1
	FAHP-ZOGP	Increased by 20 %	Route 1
	FBWM-ZOGP	Decreased by 20 %	Route 4
	FBWM-ZOGP	Increased by 20 %	Route 5
	FFUCOM-ZOGP	Decreased by 20 %	Route 5
	FFUCOM-ZOGP	Increased by 20 %	Route 5
Infrastructure risk	AHP-ZOGP	Decreased by 20 %	Route 5
	AHP-ZOGP	Increased by 20 %	Route 5
	FAHP-ZOGP	Decreased by 20 %	Route 1
	FAHP-ZOGP	Increased by 20 %	Route 1
	FBWM-ZOGP	Decreased by 20 %	Route 3
	FBWM-ZOGP	Increased by 20 %	Route 3
	FFUCOM-ZOGP	Decreased by 20 %	Route 4
	FFUCOM-ZOGP	Increased by 20 %	Route 2

Chapter 5

Conclusion, Limitation and Further study

Multimodal transportation is a popular topic among researchers due to the rising concern over the issues of road traffic and traffic safety. Many researchers have tried to address and tackle the problems related to multimodal route selection, which are considered complex multi-criteria decision making (MCDM) problems, by proposing numerous qualitative models based on subjective evaluations that take into account the uncertainty and vagueness of the human decision process. To effectively solve these dynamic problems that involve conflicting and interdependent issues, appropriate methods should be carefully chosen. This research proposes a decision support framework with the use of the combination of the FAHP method and ZOGP in order to effectively select the optimal route in a multimodal transportation system with the lowest transportation cost, time, and risks. Experts in the field of multimodal transportation were interviewed and asked to assess the weights of different factors associated with the risks within the multimodal transportation system, with the focus being on the coal transportation in Thailand. This research aims to create a mathematical model that would help select the best multimodal transportation route with the lowest cost, time, and risks. It proposes a tested conceptual framework for route selection in multimodal transportation which comprises of five main phases, which involve the LSPs analyzing the nature of risks associated with multimodal transportation using the FAHP-DEA method. The levels of risks are assessed using the quantitative risk analysis and risk matrix with a set of assessment grades in linguistic terms. The FAHP method is used to determine the weights of the criteria in consideration, the SAW method is used to aggregate local risk scores of all the decision alternatives, which are then prioritized using the FAHP method. The significance weights of criteria gained from the FAHP method are then integrated in the objective function of the ZOGP, before ending with the use of the zero-one goal programming which reveals the optimal route.

The results demonstrate that the optimal route from Srichang to Saraburi Cement Industry is Route1 with ship and truck as modes of transportation. The total cost is 120.26 USD and the total time spent is 73 hours. The risks associated with freight damage, infrastructure and equipment, operation, security, and environment are 0.561, 0.831, 0.397, 0.247, and 0.204, respectively.

This study help determines the most flexible approach that can be applied in the selection of the optimal multimodal transportation route which takes into consideration the criteria related to cost, time, and risks. Nevertheless, there are some limitations regarding the factors related to transportation cost and time which can be affected by seasonal changes. In addition, the experts who participated in the interviews were from various organizations that were different in terms of type, size, and region, meaning that they had various conflicting perspectives regarding the factors affecting route selection. Also, since the majority of data acquired as part of this research is specific to the context of the case study, the data must be adjusted before they can be applied in other cases, and the factors related to the preference scores of the experts have to be constructed carefully. Moreover, there is also a limitation with regard to the calculation of cost due to the multimodal nature of transportation routes. Therefore, the potential moderating effects such as transshipment cost, delivery cost, and insurance cost as a result of dependency or cooperation between transportation modes and distribution channels must be taken into account.

For further study, new algorithms should be developed in order to solve the problems related to multimodal transportation. These algorisms can also be applied to other complex issues concerning the multimodal route selection which would lead to an improvement in systematic decision support tool.

Publications

International Journal

1. Kaewfak K., Ammarapala V., Huynh VN, Multi-Objective Optimisation of Freight Route Choices in Multimodal Transportation, *International Journal of Computational Intelligence Systems*, 14(1), 794 – 807, 2021.

2. Kaewfak K., Huynh VN., Ammarapala V., Ratisoontorn N, A Risk Analysis Based on a Two-stage Model of Fuzzy AHP-DEA for Multimodal Freight Transportation Systems, *IEEE Access*, 8, 153756-153773, 2020.

International Conference

1. Kaewfak K., Huynh VN., Ammarapala V., Charoensiriwath C, A Fuzzy AHP-TOPSIS Approach for Selecting the Multimodal Freight Transportation Routes, The International Symposium, Knowledge and Systems Sciences, 29 November-1 December 2019, Da Nang, Vietnam.

2. Kaewfak K., Huynh VN., Ammarapala V., Charoensiriwath C, The Quantitative Risk Analysis in Multimodal Freight Transportation System: An empirical study, The International Conference on Modeling Decisions for Artificial Intelligence, 4-6 September 2019, Milan, Italy.

Bibliography

[1] SteadieSeifi, M., Dellaert, N., Nuijten, W., Van Woensel, T., Raoufi, R.: Multimodal freight transportation planning: A literature review. European Journal of Operational Research 233(1), 1–15 (2014)

[2] Min, H.: International intermodal choices via chance-constrained goal programming. Transportation Research Part A: General 25(6), 351–362 (1991)

[3] Southworth, F., Peterson, B.E.: Intermodal and international freight network modeling q p. 20 (2000)

[4] Ham, H., Kim, T.J., Boyce, D.: Implementation and estimation of a combined model of interregional, multimodal commodity shipments and transportation network flows. Transportation Research Part B: Methodological 39(1), 65–79 (2005)

[5] Zhang, X., He, Z., Pan, Y.: Study on Multimodal Transport Network Model Base on Genetic Algorithm Method. In: ICLEM 2010. pp. 3514–3520. American Society of Civil Engineers (Sep 2010)

[6] Scenna, N., Santa Cruz, A.: Road risk analysis due to the transportation of chlorine in Rosario city. Reliability Engineering & System Safety 90(1), 83–90 (2005)

[7] Verma, M.: Railroad transportation of dangerous goods: A conditional exposure approach to minimize transport risk. Transportation Research Part C: Emerging Technologies 19(5), 790–802 (2011)

[8] Kengpol, A., Tuammee, S., Tuominen, M.: The development of a framework for route selection in multimodal transportation. The International Journal of Logistics Management 25(3), 581–610 (2014)

[9] Kengpol, A., Tuammee, S.: The development of a decision support framework for a quantitative risk assessment in multimodal green logistics: an empirical study. International Journal of Production Research 54(4), 1020–1038 (2016)

[10] Yang, X., Liu, L., Li, Y., He, R.: Route Selection for Railway Passengers: A Multi-objective Model and Optimization Algorithm. Journal of Transportation Systems Engineering and Information Technology 13(5), 72–100 (2013)

[11] Zhang, H., Yuan, M., Liang, Y., Wang, B., Zhang, W., Zheng, J.: A risk assessment based optimization method for route selection of hazardous liquid railway network. Safety Science 110, 217–229 (2018)

[12] Meethom, W., Koohathongsumrit, N.: Design of Decision Support System for Road Freight Transportation Routing Using Multilayer Zero One Goal Programming. Engineering Journal 22(6), 185–205 (2018)

[13] Kumar, A., Anbanandam, R.: Development of social sustainability index for freight transportation system. Journal of Cleaner Production 210, 77–92 (2019)

[14] Elvik, R.: Does the influence of risk factors on accident occurrence change over time? Accident Analysis & Prevention 91, 91–102 (2016)

[15] Jacobsson, S., Arnäs, P.O., Stefansson, G.: Access management in intermodal freight transportation: An explorative study of information attributes, actors, resources and activities. Research in Transportation Business & Management 23, 106–124 (2017)

[16] Saeedi, H., Behdani, B., Wiegmans, B., Zuidwijk, R.: Assessing the technical efficiency of intermodal freight transport chains using a modified network DEA approach. Transportation Research Part E: Logistics and Transportation Review 126, 66–86 (2019)

[17] Hesse, M., Rodrigue, J.P.: The transport geography of logistics and freight distribution. Journal of Transport Geography 12(3), 171–184 (2004)

[18] Mathisen, T.A., Hanssen, T.E.S.: The Academic Literature on Intermodal Freight Transport. Transportation Research Procedia 3, 611–620 (2014)

[19] Forkenbrock, D.J.: Comparison of external costs of rail and truck freight transportation. Transportation Research Part A: Policy and Practice 35(4), 321–337 (2001)

[20] Macharis, C., Caris, A., Jourquin, B., Pekin, E.: A decision support framework for intermodal transport policy. European Transport Research Review 3(4), 167–178 (2011)

[21] Kengpol, A., Meethom, W., Tuominen, M.: The development of a decision support system in multimodal transportation routing within Greater Mekong sub-region countries. International Journal of Production Economics 140(2), 691–701 (2012)

[22] Chang, K.H., Cheng, C.H.: A risk assessment methodology using intuitionistic fuzzy set in FMEA. International Journal of Systems Science 41(12), 1457–1471 (2010)

[23] Soeanu, A., Debbabi, M., Alhadidi, D., Makkawi, M., Allouche, M., Bélanger, M., Léchevin, N.: Transportation risk analysis using probabilistic model checking. Expert Systems with Applications 42(9), 4410–4421 (2015)

[24] Zaman, M.B., Kobayashi, E., Wakabayashi, N., Khanfir, S., Pitana, T., Maimun, A.: Fuzzy FMEA model for risk evaluation of ship collisions in the Malacca Strait: based on AIS data. Journal of Simulation 8(1), 91–104 (Feb 2014)

[25] Landucci, G., Antonioni, G., Tugnoli, A., Bonvicini, S., Molag, M., Cozzani, V.: HazMat transportation risk assessment: A revisitation in the perspective of the Viareggio LPG accident. Journal of Loss Prevention in the Process Industries 49, 36–46 (2017)

[26] Vilko, J., Ritala, P., Hallikas, J.: Risk management abilities in multimodal maritime supply chains: Visibility and control perspectives. Accident Analysis & Prevention 123, 469–481 (2019)

[27] Hallikas, J., Lintukangas, K.: Purchasing and supply: An investigation of risk management performance. International Journal of Production Economics 171, 487–494 (2016)

[28] Wu, T., Blackhurst, J. (eds.): Managing supply chain risk and vulnerability: tools and methods for supply chain decision makers. Springer, London ; New York (2009)

[29] Banomyong, R., Beresford, A.K.C.: of Laotian garment exporters p. 24 (2001)

[30] Pallis, P.L.: Port Risk Management in Container Terminals. Transportation Research Procedia 25, 4411–4421 (2017)

[31] Chang, Y.H., Wey, W.M., Tseng, H.Y.: Using ANP priorities with goal programming for revitalization strategies in historic transport: A case study of the Alishan Forest Railway. Expert Systems with Applications 36(4), 8682–8690 (2009)

[32] Mulliner, E., Malys, N., Maliene, V.: Comparative analysis of MCDM methods for the assessment of sustainable housing affordability. Omega 59, 146–156 (2016)

[33] Velasquez, M., Hester, P.T.: An Analysis of Multi-Criteria Decision Making Methods 10(2), 11 (2013)

[34] Rostamzadeh, R., Sofian, S.: Prioritizing effective 7Ms to improve production systems performance using fuzzy AHP and fuzzy TOPSIS (case study). Expert Systems with Applications 38(5), 5166–5177 (2011)

[35] Chou, Y.C., Hsu, Y.Y., Yen, H.Y.: Human resources for science and technology: Analyzing competitiveness using the analytic hierarchy process. Technology in Society 30(2), 141–153 (2008)

[36] Daim, T., Yates, D., Peng, Y., Jimenez, B.: Technology assessment for clean energy technologies: The case of the Pacific Northwest. Technology in Society 31(3), 232–243 (2009)

[37] Unutmaz Durmuşoğlu, Z.D.: Assessment of techno-entrepreneurship projects by using Analytical Hierarchy Process (AHP). Technology in Society 54, 41–46 (2018)

[38] Rajak, M., Shaw, K.: Evaluation and selection of mobile health (mHealth) applications using AHP and fuzzy TOPSIS. Technology in Society 59, 101186 (2019)

[39] Bentes, A.V., Carneiro, J., da Silva, J.F., Kimura, H.: Multidimensional assessment of organizational performance: Integrating BSC and AHP. Journal of Business Research 65(12), 1790–1799 (2012)

[40] Ammarapala, V., Chinda, T., Pongsayaporn, P., Ratanachot, W., Punthutaecha, K., Janmonta, K.: Cross-border shipment route selection utilizing analytic hierarchy process (AHP) method p. 7 (2018)

[41] L. A., Z.: Fuzzy Sets. Information and controls 8, 338–353 (1965)

[42] Renjith, V., Jose kalathil, M., Kumar, P.H., Madhavan, D.: Fuzzy FMECA (failure mode effect and criticality analysis) of LNG storage facility. Journal of Loss Prevention in the Process Industries 56, 537–547 (2018)

[43] Wang, X., Chan, H.K., Yee, R.W., Diaz-Rainey, I.: A two-stage fuzzy-AHP model for risk assessment of implementing green initiatives in the fashion supply chain. International Journal of Production Economics 135(2), 595–606 (2012)

[44] Zyoud, S.H., Kaufmann, L.G., Shaheen, H., Samhan, S., Fuchs-Hanusch, D.: A framework for water loss management in developing countries under fuzzy environment: Integration of Fuzzy AHP with Fuzzy TOPSIS. Expert Systems with Applications 61, 86–105 (2016)

[45] Chang, D.Y.: Applications of the extent analysis method on fuzzy AHP. European Journal of Operational Research 95(3), 649–655 (1996)

[46] Wang, Y.M., Liu, J., Elhag, T.M.: An integrated AHP–DEA methodology for bridge risk assessment. Computers & Industrial Engineering 54(3), 513–525 (2008)

[47] Hadi-Vencheh, A., Mohamadghasemi, A.: A fuzzy AHP-DEA approach for multiple criteria ABC inventory classification. Expert Systems with Applications 38(4), 3346–3352 (2011)

[48] Do, Q.H., Chen, J.F.: A Hybrid Fuzzy AHP-DEA Approach for Assessing University Performance. WSEAS Transaction on Business and Economics 11, 12 (2014)

[49] Allevi, E., Basso, A., Bonenti, F., Oggioni, G., Riccardi, R.: Measuring the environmental performance of green SRI funds: A DEA approach. Energy Economics 79, 32–44 (2019)

[50] Liu, H.h., Yang, G.l., Liu, X.x., Song, Y.y.: R&D performance assessment of industrial enterprises in China: A two-stage DEA approach. Socio-Economic Planning Sciences p. 100753 (2019)

[51] Shwartz, M., Burgess, J.F., Zhu, J.: A DEA based composite measure of quality and its associated data uncertainty interval for health care provider profiling and pay-for-performance. European Journal of Operational Research 253(2), 489–502 (2016)

[52] Diouf, M., Kwak, C.: Fuzzy AHP, DEA, and Managerial Analysis for Supplier Selection and Development; From the Perspective of Open Innovation. Sustainability 10(10), 3779 (2018)

[53] Wanke, P.F.: Physical infrastructure and shipment consolidation efficiency drivers in Brazilian ports: A two-stage network-DEA approach. Transport Policy 29, 145–153 (2013)

[54] Regalado López, F.J., Campos Cacheda, J.M.: An Approximation to Technical Efficiency in Spanish Toll Roads through a DEA approach. Transportation Research Procedia 33, 386–393 (2018)

[55] Matthews, K.: Risk management and managerial efficiency in Chinese banks: A network DEA framework. Omega 41(2), 207–215 (2013)

[56] Shi, Q., Zhou, Y., Xiao, C., Chen, R., Zuo, J.: Delivery risk analysis within the context of program management using fuzzy logic and DEA: A China case study. International Journal of Project Management 32(2), 341–349 (2014)

[57] Skevas, T., Stefanou, S.E., Oude Lansink, A.: Pesticide use, environmental spillovers and efficiency: A DEA risk-adjusted efficiency approach applied to

Dutch arable farming. European Journal of Operational Research 237(2), 658–664 (2014)

[58] Ghunaim, H., Dichter, J.: Applying the FAHP to Improve the Performance Evaluation Reliability of Software Defect Classifiers. IEEE Access 7, 62794–62804 (2019)

[59] Chen, R.S., Shyu, J.Z.: Selecting a weapon system using zero-one goal programming and analytic network process. Journal of Information and Optimization Sciences 27(2), 379–399 (2006)

[60] Kim, G.C., Emery, J.: An application of zero–one goal programming in project selection and resource planning – a case study from the Woodward Governor Company. Computers & Operations Research 27(14), 1389–1408 (2000)

[61] Badri, M.A., Davis, D., Davis, D.: A comprehensive 0–1 goal programming model for project selection. International Journal of Project Management 19(4), 243–252 (2001)

[62] Noguchi, H., Ogawa, M., Ishii, H.: The appropriate total ranking method using DEA for multiple categorized purposes. Journal of Computational and Applied Mathematics 146(1), 155–166 (2002)

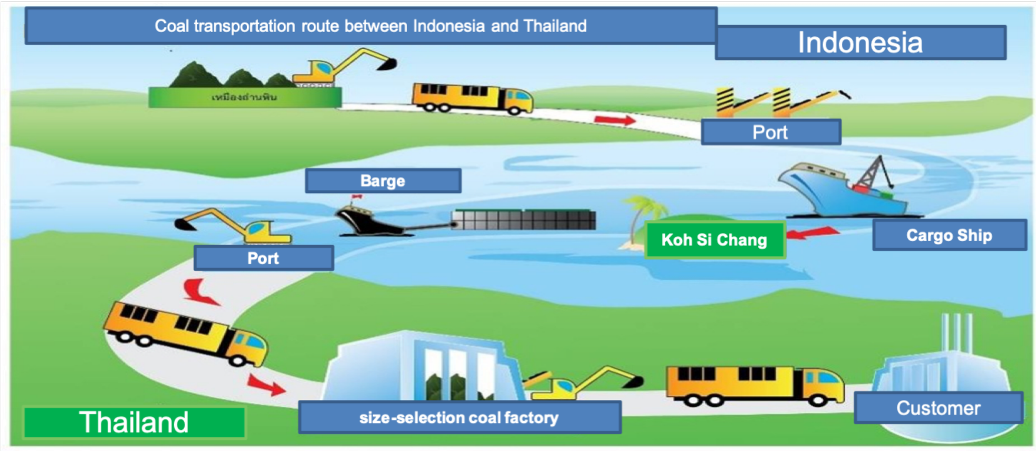


Figure 5.1: Coal logistics in Thailand

Appendix A

Logistics and Coal industry in Thailand

In Thailand, coal is mainly used as a fuel for generating electricity. As the coal is burned, it releases the heat which is used to transform the water into steam, which powers a turbine. At the moment, coal is a major fuel which is used for about 40% of electricity generation worldwide. Given that the amount of coal reserves can still be used for 200 years more, and the price of coal still remains stable and affordable, the average price of electricity in Thailand will not increase unreasonably. Nowadays, the advanced coal-fired power plant technology has made it possible to better control pollution to be below the maximum amount stated by the law. This new technology can also more effectively reduce air pollution such as sulfur dioxide (SO2), nitrogen dioxide (NOX), and carbon dioxide (CO2) than before.

Every day, coal is imported from Indonesia or Australia using 10,000-ton carriers which arrive at the harbor a couple of times per day. In order to prevent the diffusion of coal and to decrease the mixing of sludge and wave, the speed of the carriers cannot be more than 10 kilometers per hour. Furthermore, the coal transported by these carriers does not have an impact on marine attractions since its shipping route is not so close to most diving areas which are around 10 kilometers away (only 2 diving spots are about 5 kilometers away).

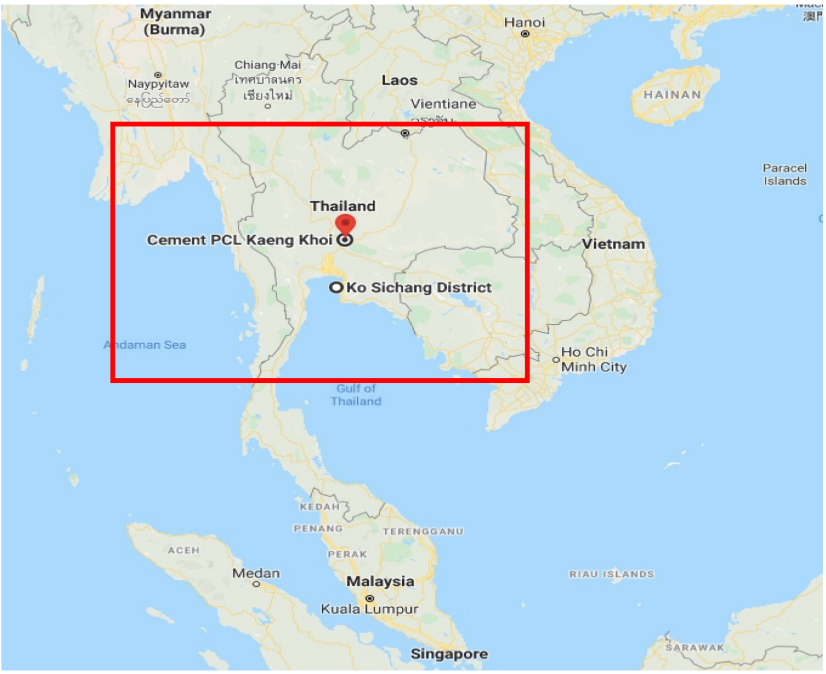


Figure 5.2: A case study map

Appendix B

Multimodal transportation routes

This research looks at a selection of routes in multimodal transportation in the central region of Thailand, with a case study focusing on the domestic freight routes from Srichang, Chonburi Province to a cement factory in Saraburi Province, as illustrated in Figure 5.2. There are three transportation modes within these routes which are rail, ship, and truck. The experts in the field have informed that 8 transportation routes exist as can be seen in Figures 5.3-5.10. The detail of each route is demonstrated below.

Route 1: A-1-5-18-B (Ship and truck)
Route 2: A-1-6-13-18-B (Ship and truck)
Route 3: A-2-7-14-23-B (Ship and truck)
Route 4: A-2-8-15-19-20-23-B (Ship, train and truck)
Route 5: A-3-9-16-20-23-B (Ship, train and truck)
Route 6: A-3-10-17-23-B (Ship and truck)
Route 7: A-4-21-B (Ship and truck)
Route 8: A-4-12-22-B (Ship and truck)

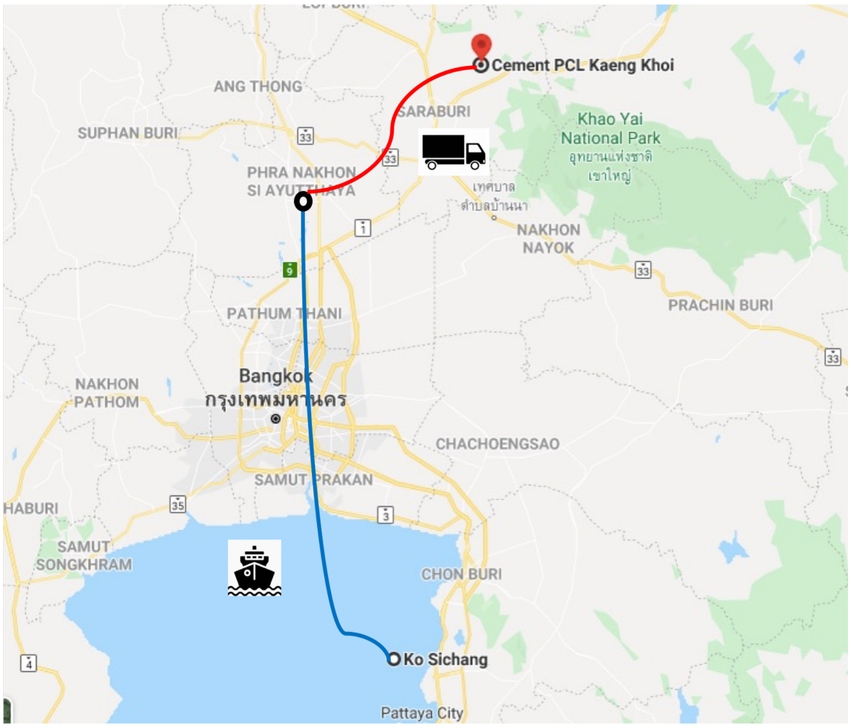


Figure 5.3: Route 1

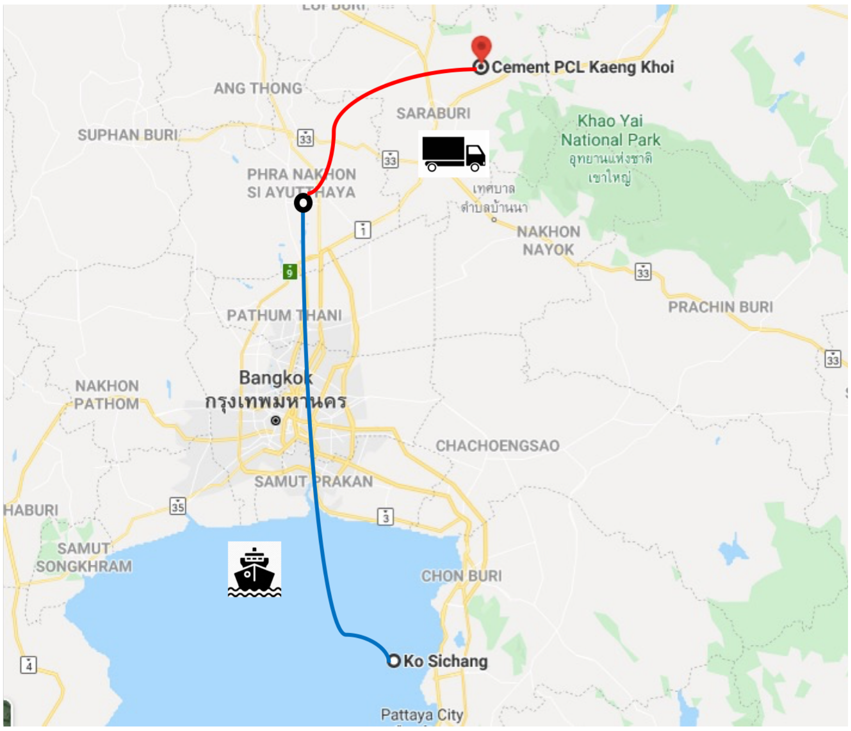


Figure 5.4: Route 2

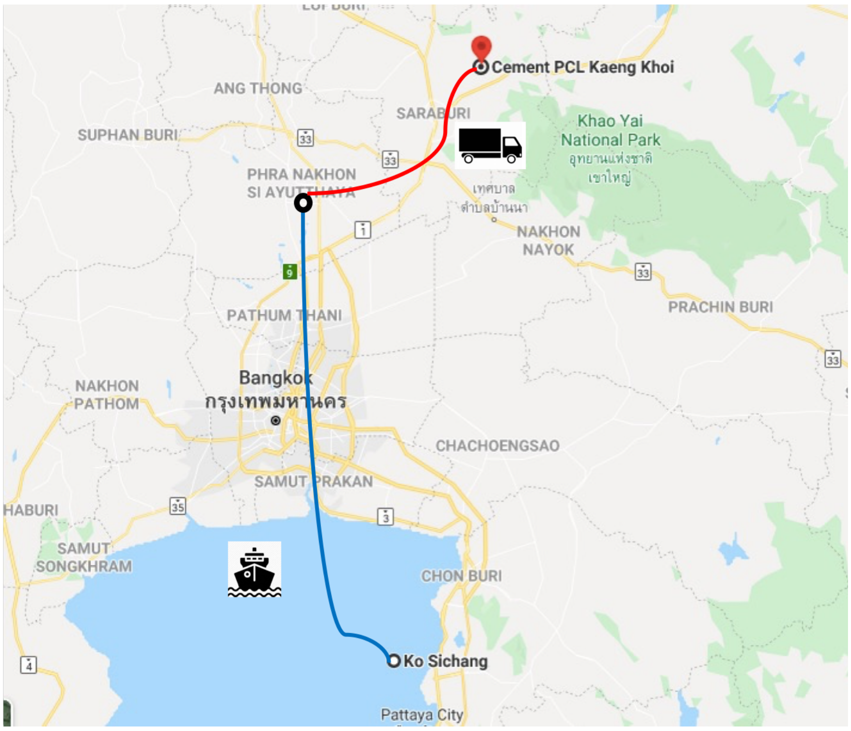


Figure 5.5: Route 3

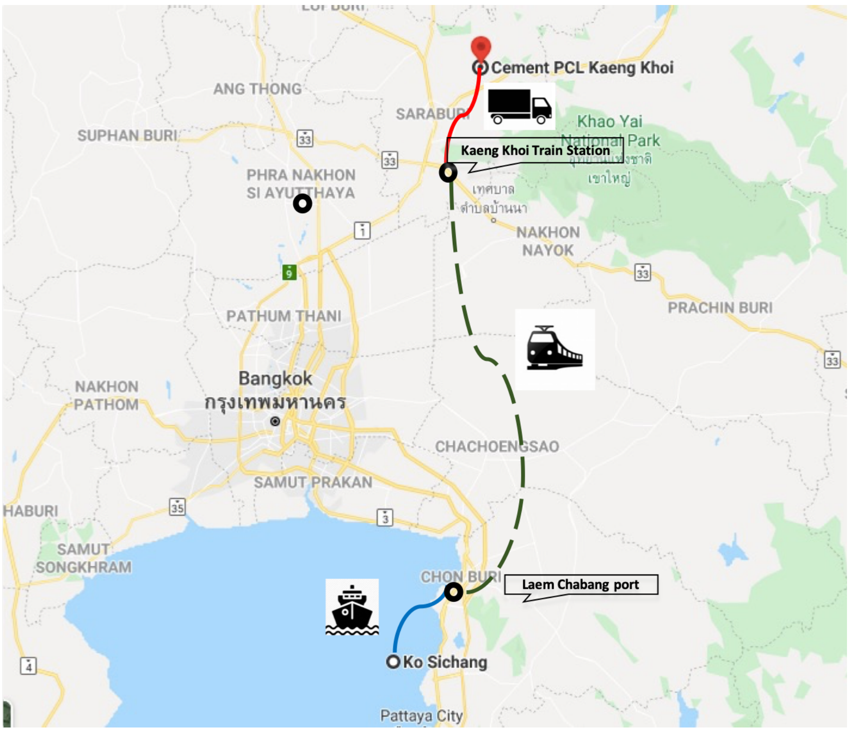


Figure 5.6: Route 4

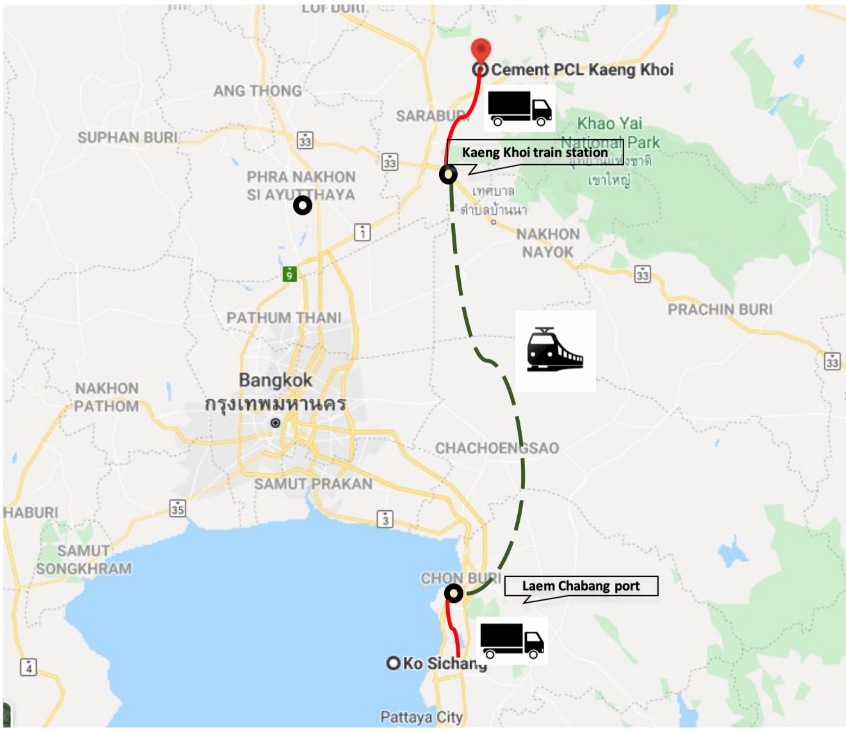


Figure 5.7: Route 5

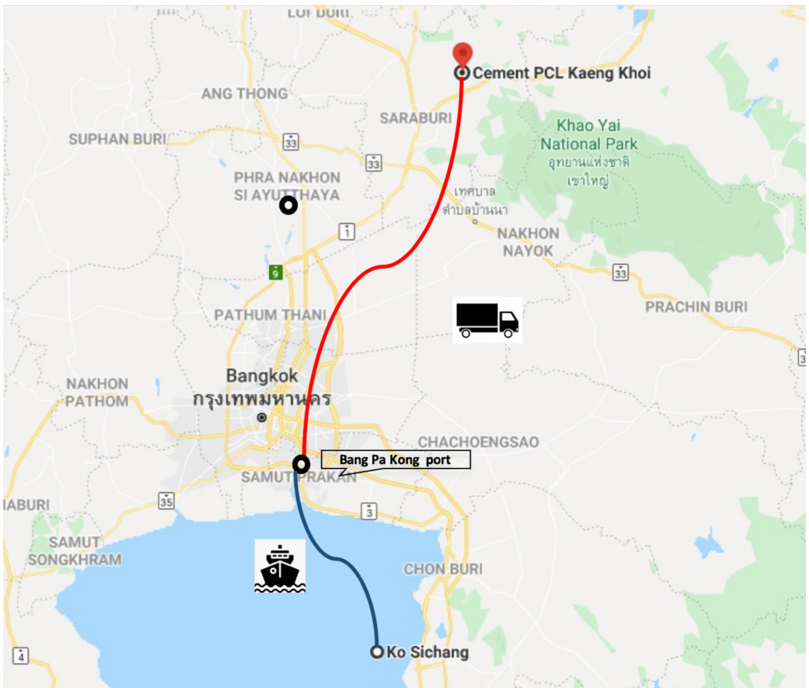


Figure 5.8: Route 6

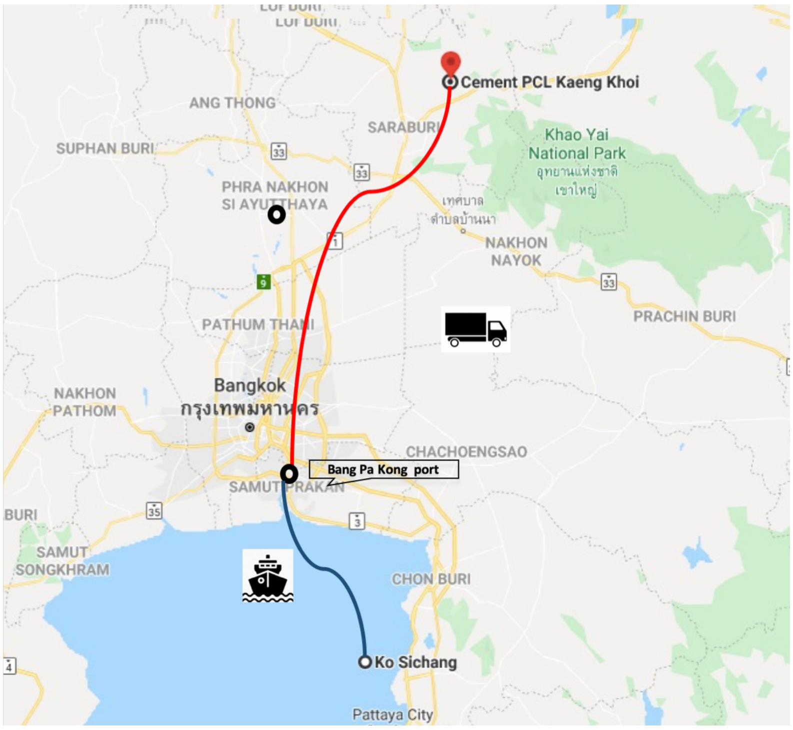


Figure 5.9: Route 7

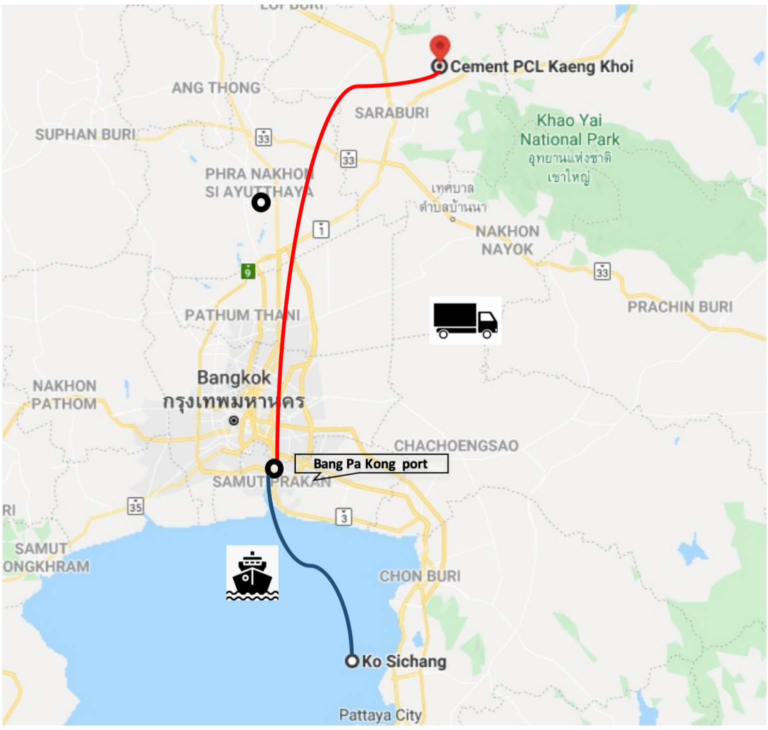


Figure 5.10: Route 8

Appendix C

ILOG CPLEX optimization software

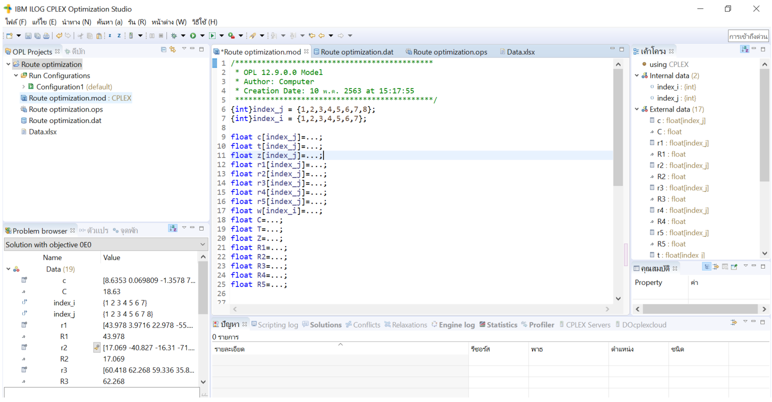


Figure 5.11: ILOG CPLEX optimization software(1)

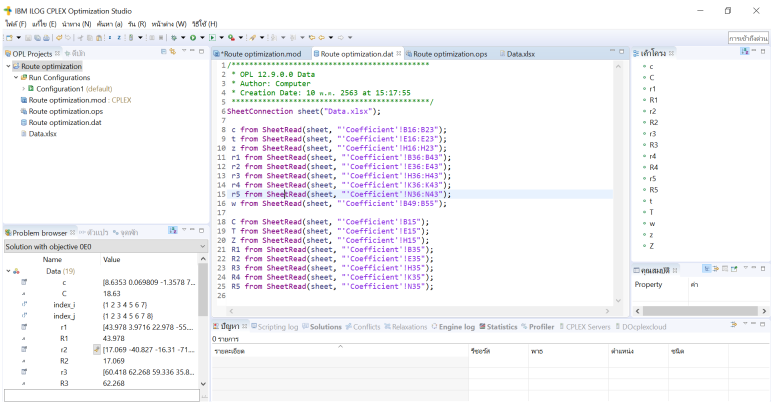


Figure 5.12: ILOG CPLEX optimization software (2)

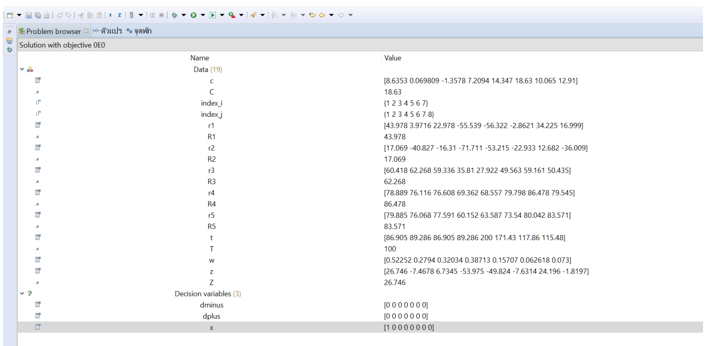


Figure 5.13: ILOG CPLEX optimization software (3)

Appendix D

Questionnaire Survey

Questionnaire Survey
Multi-objectives Optimizations for Multimodal Coal Logistics and Transportation Network

Dear Participants,

I am in the process of researching about the multimodal transportation and coal logistics in Thailand. The research focuses on the factor assessment and adaptation options. As part of this research, a multi-criteria analysis has to be conducted to obtain the opinions of the stakeholders in order to evaluate adaptation alternatives. The aim of this study is to create a multi-objectives optimization model for coal logistics which will be able to assist firms in their reduction of cost, lead time, and risks concerning the transportation of coal in Thailand. Three realistic multimodal transportation scenarios are tested. This research will develop a flexible fuzzy multi-criteria decision making (MCDM) method that can be applied by stakeholders in their selection of the optimal multimodal transportation route.

In the next pages, please provide your expert opinions via a questionnaire survey. You will be asked to prioritize a list of factors according to the criteria and goal of the project. Your information will be valuable for this study. I greatly appreciate your participation. Thank you for your time.

Kwanjira Kaewfak
PhD Student
School of management technology
Sirindhorn International Institute of Technology, Thammasat University
School of Knowledge Science
Japan Advanced Institute of Science and Technology

Questionnaire Survey

Multi-objectives Optimizations for Multimodal Coal Logistics and Transportation Network

Goal: : To search for the best multimodal transportation route.

Criteria: 3 criteria and 5 sub-criteria were selected in the FAHP evaluation:

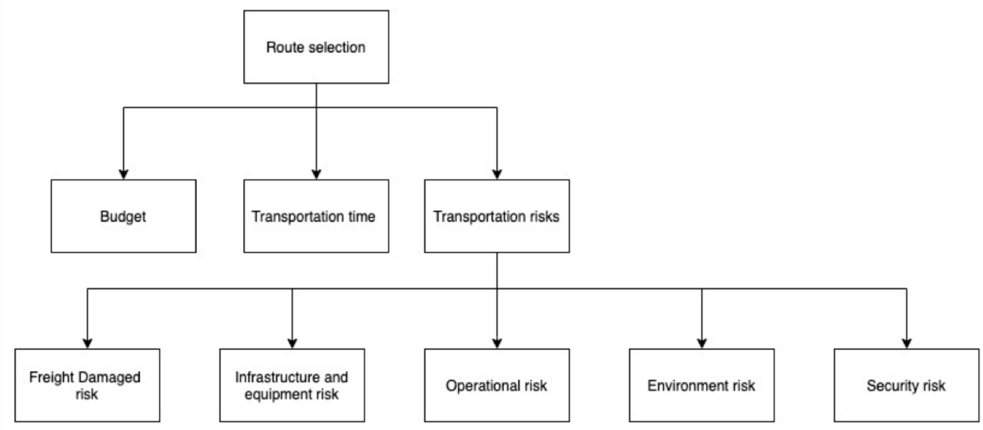
1. Transportation cost: The transportation cost varies on different routes. The cost parameters comprise of the costs related to transshipment, operation, investment, transit, as well as loading and unloading costs.

2. Transportation time: This is a very important factor when assessing the benefits of the investment related to transportation infrastructure. The purposes of this type of investment is usually connected to the reduction of time used in freight transportation. However, particular rules that aim at enhancing safety may slow down travel. Transportation time is related to the loading and unloading time as well as transit and transshipment time.

3. Transportation risk: Within a decision-making process, risk is a crucial factor. It is related to the accidents that lead to higher direct cost, and in turn, to a lower competitive advantage. In this study, transportation risks refer to the risks related to freight damage, infrastructure, operation, environment, and security.

5 Sub-criteria of risks

1. Freight Damage: This type of risk is related to the loss or damage of products



while they are being transported and delivered to the warehouse or the customer.

2. Infrastructure and equipment: This is the type of risk associated with traffic, capacity of bridges, tunnels, and ports as well as the transit utilization, etc.

3. Operation: This type of risk is associated with the document and contract related problems as well as the lack of skilled labor.

4. Security: One way to prevent terrorism is to have a secure transportation system since, may times, terrorists might use or target transportation facilities, taking into account a transportation element in their overall plan. Therefore, a security planning must take the security of the transportation system seriously. The security risk refers to the probability of an incident attempt multiplied by the target's vulnerability multiplied by the cost of damage.

5. Environment: This type of risk is associated with the probability of an event that leads to a possible undesirable impact. Quantitative risk assessment is statistical since it is the mathematical measure of risk that determines the adverse impact. This type of risk includes natural disasters and climate related conditions such as floods, storms, carbon released along the route, etc.

Questionnaire Survey

Multi-objectives Optimizations for Multimodal Coal Logistics and Transportation Network

In the next pages, please provide your opinions regarding on each item using the provided pair wise comparison scale to determine the significance of one element as opposed to another.

Description	Number Values
If option A and option B are equally important	1
If option A is moderately more important than option B	3
If option A is strongly more important than option B	5
If option A is very strongly more important than option B	7
If option A is extremely more important than option B	9
Use even numbers for intermediate judgements	2, 4, 6, 8

Regarding the sub-criteria risk, use the scale from 1 to 9 (9 means 'extremely important' and 1 means 'equally important'). Please write down (x) to determine the importance of option A in the left column in relation to option B in the right column.

A options	extremely		very strongly		Strongly		Moderately		Equally		Moderately		Strongly		very strongly		extremely	B options
Freight Damaged Risk	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Infrastructure and Equipment Risk
Freight Damaged Risk	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Operational Risk
Freight Damaged Risk	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Security Risk
Freight Damaged Risk	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Environmental Risk
Infrastructure and Equipment Risk	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Operational Risk
Infrastructure and Equipment Risk	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Security Risk
Infrastructure and Equipment Risk	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Environmental Risk
Operational Risk	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Security Risk
Operational Risk	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Environmental Risk
Security Risk	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Environmental Risk

Questionnaire Survey

Multi-objectives Optimizations for Multimodal Coal Logistics and Transportation Network

Regarding the goal (optimization), using the scale from 1 to 9 (9 means 'extremely important' and 1 means 'equally important'). Please write down (x) to determine the importance of option A in the left column in relation to option B in the right column.

A options	extremely		very strongly		Strongly		Moderately		Equally		Moderately		Strongly		very strongly		extremely	B options
Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Time
Cost	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Risk
Time	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Risk

Factors	Rating Scale				
	1	2	3	4	5
Accident rate					
Route restrictions					
Infrastructure limitation					
Lack of multimodal equipment					
On-time/on-budget delivery					
Demand volatility					
Lack of skilled workers					
Damaged in transportation					
Traceability on reverse logistics					
Cargo being stolen					
Fire					
Natural disaster					

Figure 5.14: Questionnaire survey of 5 point likert scale

Factor Analysis

Factor Analysis (FA) is a popular multivariate statistical tool for analyzing data. In general, Likert measurement scales are often used to obtain variables correlations and variances related to the mean values. Factor Analysis focuses on the subsets of highly connected variables that link to the lower levels of Likert scales, meaning the lack of the measured features which means that the loading vectors might be meaningless for interpretation

In this study, 12 qualitative risk factors are presented in the questionnaire. In the first step, 5-point Likert scale (1 means "the least significant" and 5 means "the most significant") is used in the process of selecting the qualitative factors related to the multimodal transportation. These factors are determined using the information from the previous studies as well as from the interview with the experts in the field of cement industry and logistics.