Risk Assessment in LPG Chain: A Case Study

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CERTIFICATE OF APPROVAL

The project titled "Risk Assessment in LPG Chain: A Case Study" submitted by Zisan Munsur, Roll No.: 0417082104, Session: April-17, has been accepted as satisfactory in partial fulfillment of the requirement for the degree of **Master of Engineering in Advanced Engineering Management** on August 05, 2023.

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It is hereby declared that this project or any part of it has not been submitted elsewhere for the award of any degree or diploma.

Zisan Munsur

This Work is Dedicated to My Parents

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List of Abbreviations

LPG	: Liquified Petroleum Gas
MCDM	: Multi-criteria Decision Making
AHP	: Analytic Hierarchy Process
TOPSIS	: Technique for Order of Preference by Similarity to Ideal Solution
PROMETHEE	: Preference Ranking Organization Method for Enrichment Evaluation

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Abstract

Liquified petroleum gas (LPG) plays a vital role in the energy sector throughout the world and in Bangladesh. However, the Post-COVID-19 era and the ongoing Russia-Ukraine war caused energy supply disruption globally. The LPG supply chain is also exposed to various risk factors. Therefore, this study aims to identify the major risk factors and prioritize them to improve the resilience of the LPG supply chain. In the study, Multi-criteria decision-making (MCDM) techniques including Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), and Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) methods were used. AHP-TOPSIS and AHP-PROMETHEE, these two integrated combinations were used to verify the robustness of the study result. The study reviewed the literature to find the risk prioritizing criteria and the risk factors, and also take input from the experts. This study selected six criteria and 17 risk factors. Using the experts' opinion, the AHP found "Impact on business" and "Probability of occurrence" are the two most weighted criteria for LPG supply chain risk prioritization. "Price fluctuations due to changes in demand or supply, geopolitical events, or regulatory changes", "Cybersecurity breaches including hacking, malware, and other types of cyber-attacks", and "Economic or financial crises leading to changes in demand and supply" have been identified as the topmost three risks in both AHP-TOPSIS and AHP-PROMETHEE combination. This study provides insights for managers and policymakers to improve LPG supply chain resilience in the post-pandemic era and during the global political crisis.

Chapter -1 Introduction

1.1. Introduction

The liquefied petroleum gas (LPG) industry plays a crucial role in meeting the energy demands of various sectors worldwide (Bariha et al., 2023). It is a clean, efficient, and versatile fuel that can be used for cooking, heating, and powering vehicles, among other applications (Mani et al, 2020; Dalaba et al., 2018). LPG is also a critical component in many chemical and petrochemical processes, making it a crucial raw material in the industrial sector (Thompson et al., 2021). In addition, LPG is a cost-effective energy source, especially for remote and rural areas that lack access to other energy sources such as electricity and natural gas (Asante et al., 2021; Shupler et al., 2021). The portability of LPG makes it an essential source of energy for emergency and disaster relief efforts. However, the supply chain of LPG is vulnerable to a variety of risks such as natural disasters, political instability, and economic downturns (Cui et al., 2023; Urciuoli et al., 2014). The COVID-19 pandemic has further exacerbated these risks and highlighted the need for enhancing the resilience of the LPG supply chain (Zakeri et al., 2022). The ongoing Russia-Ukraine war and the global energy crisis have added to the already complex and dynamic environment of the LPG supply chain. Policymakers are concerned about the impact of these risk factors on the availability and stability of LPG supplies (Allam et al., 2022). In light of these challenges, examining the implications of risk analysis in enhancing the resilience of the LPG supply chain in the existing international political crisis and post-COVID-19 era can play a significant role.

A supply chain refers to the interconnected network of organizations, activities, information, and resources involved in the production and delivery of a product or service from the raw materials stage to the end customer (Karmaker et al., 2023). It encompasses all the steps involved in the production, transportation, and delivery of a product, from sourcing raw materials to delivering the finished product to the customer (Karmaker et al., 2021). The LPG supply chain, specifically, refers to the series of processes and organizations involved in the production, storage, transportation, and delivery of liquefied petroleum gas. This includes the exploration and production of natural gas, refining of crude oil into propane and butane, storage and transportation of

LPG by tanker ships, storage and distribution at terminals, and delivery to end customers such as households, industrial users, and retailers (Makhanda et al., 2019; Hossain et al., 2015). The LPG supply chain also involves various stakeholders, including suppliers, manufacturers, distributors, and customers, who work together to ensure a seamless and efficient delivery of LPG.

The resilience of a supply chain refers to its ability to recover and adapt in the face of unexpected disruptions or risks. Risk analysis helps identify potential risks and prioritize mitigation strategies to enhance the resilience of the supply chain (Moktadir et al., 2018). Supply disruptions of LPG can have far-reaching effects on both the energy and economic sectors. When LPG supplies are disrupted, it can cause shortages of this important fuel source, leading to higher prices and reduced availability (Pourhejazy et al., 2017). This, in turn, can have a significant impact on households and industries that rely on LPG for cooking, heating, and other applications. In the energy sector, supply disruptions of LPG can lead to a reduction in the production of electricity and other forms of energy that rely on LPG as a fuel source. This can result in power outages, lower production levels, and reduced competitiveness for businesses operating in the energy sector (Himawan, 2023). In the economic sector, supply disruptions of LPG can lead to increased costs for households and businesses that rely on LPG for energy. This can reduce the disposable income of households and make it more difficult for businesses to operate and compete in the market (Cui et al., 2023). Supply disruptions can disrupt the operations of industries that rely on LPG as a raw material, leading to lower production levels, reduced competitiveness, and lost revenue. To mitigate these risks, it is important to implement effective risk management strategies and improve the resilience of the LPG supply chain.

Amid this situation, some research questions arise, such as-

RQ1) What are the significant risk factors that affect the resilience of the LPG supply chain during global political crises and the post-pandemic era?

RQ2) What criteria can be used to prioritize the identified risk factors and develop a hierarchical approach to mitigate them?

RQ3) How can a prioritization framework be developed under the current circumstances?

In the residential sector of Bangladesh, LPG is widely used for cooking and heating, especially in urban areas where access to electricity and other forms of energy is limited. In the industrial sector, LPG is used as fuel for a variety of applications, including brick kilns, food processing, and textiles (Murshed et al., 2021; Hossain et al., 2015). Additionally, LPG is an important raw material for the production of fertilizers, which are crucial for the country's agriculture sector (Rahman et al., 2017). In recent years, the Bangladesh government has been promoting the use of LPG as a cleaner and more efficient alternative to traditional fuels such as kerosene and firewood. This is in line with the country's efforts to reduce greenhouse gas emissions and improve air quality (Murshed et al., 2021). The government has also been taking steps to improve the infrastructure and supply chain of LPG, including the construction of storage terminals and the expansion of the distribution network. The current value of the LPG market in Bangladesh is over 3.2 billion USD, with 30 companies operating in the sector. The market is expected to continue growing in the coming years (Mithu, 2022).

Despite the importance of LPG in both the energy and economic sectors, there has been limited research conducted to analyze the supply chain risk factors of LPG and identify effective resilience strategies. Several recent studies have described issues related to supply chain disruptions caused by COVID-19 and the Russia-Ukraine war, or various aspects of LPG use, manufacturing, and transportation operations (Bariha et al., 2023; Cui et al., 2023; Ganesh and Kalpana, 2022; Murshed et al., 2021; Shupler et al., 2021; Mani et al., 2020; Makhanda et al., 2019; Asante et al., 2018; Rahman et al., 2017; Pourhejazy et al., 2017). However, none have specifically intended to identify and prioritize LPG supply chain risks in the present global political crisis and post-pandemic era. This lack of research is a concern, as supply chain disruptions can have serious consequences for both households and businesses that rely on LPG. Furthermore, as the demand for LPG continues to grow, the risk of supply chain disruptions will become increasingly significant.

To address this gap in the literature, researchers and industrial policymakers must conduct more extensive research into the supply chain risk factors of LPG and identify effective resilience strategies. Therefore, this research aims to identify the existing risk factors in the LPG industry and prioritize them with a hybrid multi-criteria decision-making (MCDM) approach utilizing the Analytic Hierarchy Process (AHP) and

Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method. Further, for checking the robustness of the obtained result through AHP-TOPSIS hybridization, the Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) with AHP (integrating AHP and PROMETHEE) is going to be applied.

AHP is a structured and quantitative method that provides a mathematically rigorous approach to decision-making and is favorable to the researcher for its calculation simplicity (Bari et al., 2022). TOPSIS and PROMETHEE are other two popular techniques for taking optimal decisions among multiple alternatives (Durak et al. 2022; Mokhtar et al., 2015). In hybrid MCDM techniques, AHP is largely used for determining the weightage of the criteria and TOPSIS is used to find the ultimate ranking (Li et al., 2022; Durak et al. 2022; Bari et al., 2022; Abdulvahitoglu and Kilic, 2022; Menon and Ravi, 2022). Similarly, when the hybridization is done with the AHP-PROMETHEE, AHP finds the criteria weights and PROMETHEE determines the ranking (Krouska et al., 2022; Dadrasajirlou et al., 2022; Amallynda et al. 2022; Ziemba and Gago, 2022; Rachman et al., 2022).

1.2. Objectives of the Present Work

This research, thereby, is going to achieve the following research objectives, which can help improve the resilience of the LPG supply chain and decrease the risk of supply chain disruptions:

RO1. To identify the risk factors existing in the LPG supply chain.

RO2. To determine the risk factors prioritization criteria.

RO2. To offer a framework for decision-making utilizing TOPSIS and PROMETHEE.

1.3. Organization of the Project Report

The rest of the project report is constructed as, Chapter 2 will review the existing literature on LPG and LPG supply chain, Chapter 3 will depict the methodology of the applied techniques in this project, Chapter 4 describes data collection and calculations to present a case application of LPG industry to analyze supply chain risks, Chapter 5 will discuss the obtained results from this study, Chapter 6 will highlight the implications of the study for the managers and policymakers. Finally, Chapter 7 will conclude the project by presenting the unique results from this study, the research gap, and some future research directions. References and appendix are presented at the end of the project report.

Chapter -2 Literature Review

2.1. Supply Chain Risk

The current crises due to the impact of COVID-19 and the Russia-Ukraine war are causing a rise in commodity and labor prices, affecting global energy supply chain resilience negatively and making it more difficult for developing countries (Allam et al., 2022). Bangladesh is facing significant challenges related to energy shortage in both its power sector and household activities, prompting efforts to shift towards the use of LPG as an energy source (Mithu, 2022). However, decision-makers are facing several obstacles, as revealed in the existing literature on the supply chain of LPG and other related sectors, which are impeding progress.

Karmaker et al. (2023) found that the active involvement of senior managers and financial support from investors and the government can help decision-makers to improve supply chain resilience. In a descriptive study, Shih (2020) depicted the importance of uncovering and addressing the hidden risks, identifying the vulnerabilities, diversifying the supply base, holding intermediate inventory or safety stock, investing in automated technologies and artificial intelligence in the supply chain network to be more protected in supply chain management in the post-pandemic era. Klöckner et al. (2022) agreed that the COVID-19 pandemic has caused worldwide sudden changes in supply and demand and internal production disruptions. That paper claimed, digital technologies such as blockchain, digital platforms, analytics, and digital twins can help create more resilient supply chains that can better handle future large-scale disruptions.

Andiappan et al. (2021) indicated the COVID-19 pandemic is a cause of disruption for the energy sector, prompting a need for alternative energy resources. The paper identified to development of specific areas such as supply availability, digitalization and automation, collaboration within the supply chain, community-focused energy production, social challenges and opportunities, and policy to be more resilient in the energy supply chain. Zakeri et al. (2022) analyzed the impacts of the COVID-19 pandemic and Russia's war on Ukraine on the global economy, with a specific focus on the energy sector. They emphasized overcoming the challenges toward achieving resilient and sustainable energy systems, rather than finding a short-term solution.

bin Ramlee (2022) conducted a literature review to identify factors that can influence the performance of supply chain management of LPG, such as environmental uncertainty, information technology, supply chain relationships, and customer satisfaction and suggested developing risk analysis-based strategies to enhance supply chain management performance in the LPG market. Conducting descriptive research with a semi-structured interview response, Sangeetha (2020) concluded that the supply and demand for LPG play a vital role in daily household activities and a delay in delivery affects customer satisfaction negatively.

2.2. Supply Chain Risk Resilience

Alghababsheh et al. (2023) found that improving suppliers' internal social performance can reduce supply operational risks. Hasan et al. (2023) demonstrated that closed-loop supply chains can mitigate production shortages stemming from supply chain disruptions and can lower costs, energy consumption, greenhouse gas emissions, and waste generation. Moktadir et al. (2022) identified reconfigurability, supplier relationships, health protocols, government support, and stable material supply can be the best enabler to overcome disruptions in the supply chain for COVID-19 and be resilient. Ahmed et al. (2023) examined the potential of artificial intelligence (AI) technologies to improve supply chain resiliency and sustainability in the context of the COVID-19 pandemic's impact on emerging economies' global supply chains. The study suggested that real-time tracking of supply chain activities using the Internet of Things (IoT) is the most important imperative in addressing the impacts of large-scale disruptions in the post-COVID-19 era.

2.3. LPG Supply Chain Risk Management

Bariha et al. (2023) showed, with the increase in transfer operations due to the growing demand for LPG, accidents during the transfer could have serious consequences, such as fires and explosions, which can further create severe disruptions in the supply chain. Shupler et al. (2021) examined the factors that determine the usage and consumption of LPG for cooking and found that supply-side factors such as cylinder refill and transportation costs, as well as stove equipment, are more important predictors of LPG usage and consumption than household socio-economic status. The study also emphasized the need for policies that promote LPG supply to overcome the energy crisis in rural areas.

Gallab et al. (2017) proposed an approach and analyze the risks associated with maintenance activities in an LPG supply chain as they emphasized a comprehensive view of maintenance activities in the supply chain can guide risk-minimizing decisions, thus increasing the supply chain resilience. Mittal et al. (2018) highlighted the importance of an integrated and seamless computerized monitoring system, ensuring cybersecurity, capping of entitlements, and collaboration across stakeholders for value creation to have a resilient supply chain of LPG.

2.4. Application of Multi-Criteria Decision-Making Technique

Based on the above discussion on the existing literature on supply chain risk analysis in various industries, including the LPG sector, it can be seen that those studies have not prioritized risk factors associated with local or global LPG supply chains in the context of the present political crisis and post-pandemic era. Additionally, no study has applied the AHP-TOPSIS integration or AHP-PROMETHEE integration methods for supply chain risk analysis. This research gap presents an opportunity for novel contributions to the literature. To address this gap, the current study aims to prioritize risk factors associated with LPG supply chains and apply AHP-TOPSIS and AHP-PROMETHEE integration for risk analysis. MCDM techniques are the best solutions in cases where empirical data is not readily available due to the novel pattern of the problem, and expert opinions can be taken into account for analysis and future reference (Sotoudeh-Anvari, 2022). Different MCDM techniques have their own unique advantages and limitations (Zavadskas et al., 2014). However, it is always important to ensure that the questionnaire is clearly understandable to the decision-makers, the calculations are less complex, and the outcome is consistent (Henig and Buchanan, 1996). All of these criteria are fulfilled by the AHP, TOPSIS, and PROMETHEE methods, which are favorite tools among researchers in the existing literature (Turcksin et al., 2011; Tyagi et al., 2014; Sindhu et al., 2017; Isa et al., 2021; Bari et al., 2022). Therefore, this study applies these techniques to find a robust result for the LPG supply chain risk analysis problem.

2.5. Summary of the Literature Review

The literature review highlights several related studies on various aspects of the supply chain in different industries, which are summarized in Table 2.1.

Table 2.1. Summary of the literature review

Author(s)	Study context	Study method	Outcome
Ahmed et al. (2023)	The supply chain of the post-pandemic era	Pareto analysis, bayesian approach, best-worst method	Emphasizing the use of AI-based techniques for supply chain management can lead to improved resilience
Alghababsheh et al. (2023)	Apparel supply chain	Partial least squares structural equation modeling	Improving the internal social performance of suppliers can reduce operational risks in the supply chain
Bariha et al. (2023)	LPG supply chain	Empirical method	Growing LPG demand increases transfer operations, but accidents during transfer could cause fires or explosions and disrupt the supply chain
Cui et al. (2023)	Energy supply chain during the war	Economical analysis with descriptive statistics	Analyzing the macroeconomic impact of energy interruption caused by the Russo-Ukrainian war reveals that developed countries will suffer heavy economic costs
Karmaker et al. (2023)	The supply chain of the post-pandemic era	Best worst method, Interpretive structural modelling	Senior managers' active involvement, financial support and funding from investors and the government, and the classification of challenges are crucial for managing future disruptions
Amallynda et al. (2022)	Garment industry	AHP, PROMETHEE	Analyzing the weights of criteria and sub-criteria of the supplier with the AHP method, the best supplier was selected with the PROMETHEE method
bin Ramlee (2022)	LPG supply chain	Descriptive study	Universal access to LPG can aid in socio-political and economic development, whereas environmental uncertainty, information technology, supply chain relationships, and customer satisfaction are the most crucial factors that can affect the LPG supply chain
Ganesh and kalpana (2022)	Supply chain risk management	Descriptive study	The field of supply chain risk management is going to be highly dependent on artificial intelligence and machine learning to better identify, assess, mitigate, and monitor risks in the supply chain.

Author(s)	Study context	Study method	Outcome
Klöckner et al. (2022)	The supply chain of the post-pandemic era	Descriptive study	Challenges that firms face due to the COVID-19 pandemic can be mitigated by digital technologies to help decision-makers better adapt to dynamic changes in supply and demand and manage internal production disruptions
Menon and Ravi (2022)	Electronics supply chain	AHP, TOPSIS	Human rights, safety systems, pollution control, resource reduction, and transparency in suppliers' business are some of the most weighted criteria determined by the AHP, while the best sustainable supplier was selected by the TOPSIS method
Moktadir et al. (2022)	The footwear supply chain of the post-pandemic era	Best worst method	Drivers for improving the resilience of the footwear industry in the post-pandemic era are related to reconfigurability, supplier relationships, health protocols, government support, and material supply stability
Andiappan et al. (2021)	Post-pandemic biomass supply chain	Descriptive study	Maintaining supply availability, digitalizing and automating the collaboration within the supply chain, and community-focusing in energy production are the most critical points for energy supply resilience
Karmaker et al. (2021)	The supply chain of the post-pandemic era	Pareto analysis, Total interpretive structural modelling	Financial support from the government and supply chain partners is required to tackle immediate shocks on the supply chain due to COVID-19, while policy development considering health protocols and automation is essential for long-term sustainability
Mani et al. (2020)	LPG supply chain	Descriptive statistics	Rural area penetration of LPG can develop the overall energy scenario of an emerging economy while integrating cooking fuel policies with rural development for a complete transition to cleaner fuels can be helpful for a resilient supply chain
Makhanda et al. (2019)	LPG supply chain	Descriptive statistics	Supply chain disruptions in the LPG industry result in shortages of products, delays in deliveries, dissatisfied customers, disagreements over contracts, legal issues, and a negative image of the organization
Dalaba et al. (2018)	LPG supply chain	Regression analysis	LPG adoption is low in rural households whereas affordability and safety concerns are barriers to LPG adoption

Author(s)	Study context	Study method	Outcome
Moktadir et al. (2018)	Pharmaceutical supply chain	Delphi, AHP	Supply-related risks should be prioritized over operational, financial, and demand-related risks
Gallab et al. (2017)	LPG supply chain	Computer simulation	A comprehensive understanding of maintenance activities can guide decision-making toward minimizing risks associated with such activities in the supply chain

Chapter -3 Research Methodology

3.1. Research Design

The methodological framework designed for this study includes the formation of the expert panel, reviewing the literature for identifying the criteria and the risk factors, and applying the AHP, the TOPSIS, and the PROMETHEE methods for determining the prioritization of the risks. Figure 3.1 is depicting the methodology of this research.

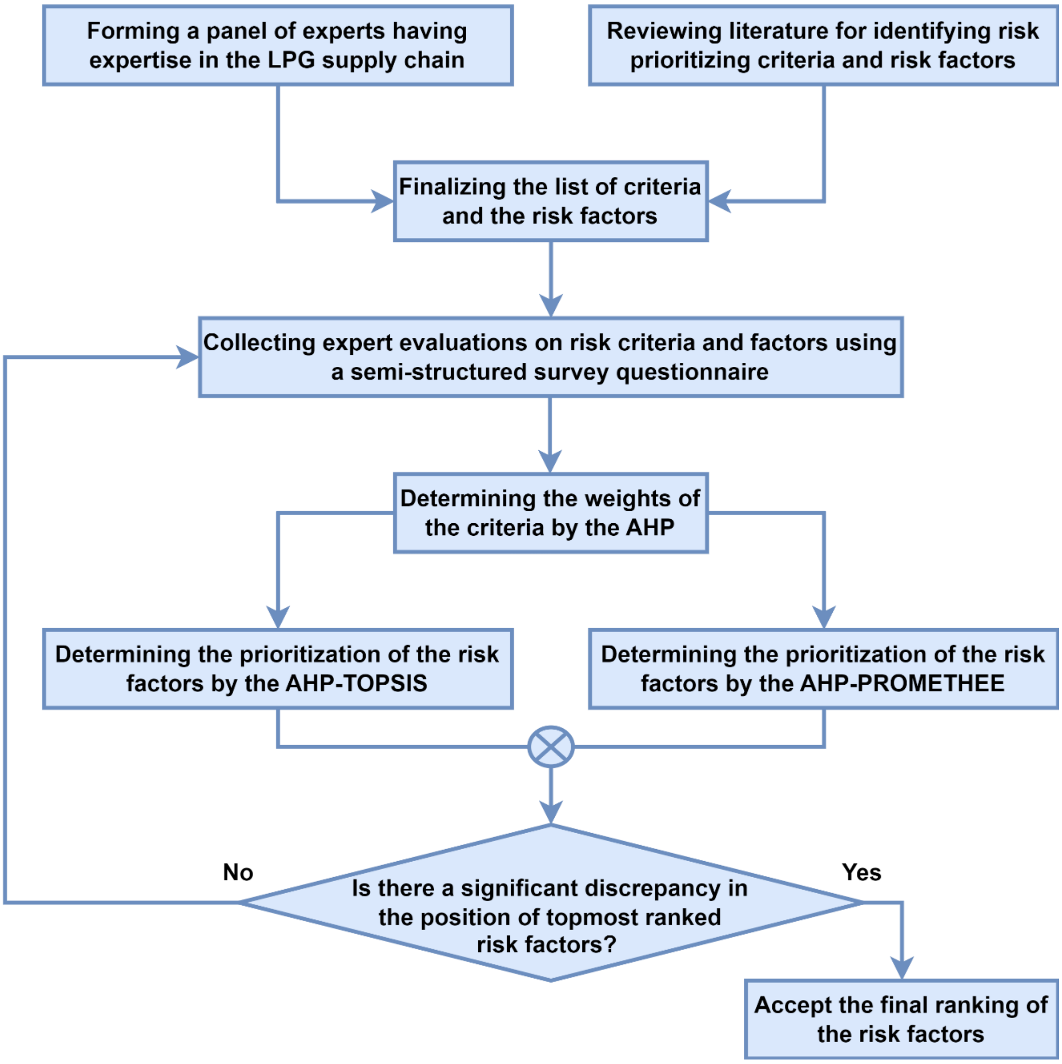

Figure 3.1. Research methodology

3.1.1 Forming the Panel of Experts

For this study, a total of 54 experts were initially approached. Eventually, 37 experts (68% of those approached) were selected purposively to participate in the expert panel for this study. In MCDM studies purposive selection of the experts is a common practice rather than random selection to utilize the relevant expertise of the experts properly and to be aligned with the study's objectives (Bari et al., 2022). The number of responding experts in such types of study may vary from a single expert to several (Zolghadr-Asli et al., 2021). The inclusion criteria for selecting the experts were as follows: a minimum of 5 years of experience working in the LPG sector, a clear understanding and knowledge of supply chain and supply chain risks, familiarity with modern supply chain and digitalization, ability to comprehend the semi-structured questionnaire, and willingness to modify or participate in multiple stages of evaluation to ensure consistency of the results. The name and working organizations of the experts are kept confidential. Table 3.1 is showing a brief profile of the experts.

Table 3.1. Brief profile of the 37 experts

Experts' designation	Year of experience	Number of experts	Percentage of the total
Head of operations	15-20 years	7	18.9%
General manager	10-15 years	8	21.6%
Supply chain manager	5-10 years	10	27.0%
Operations manager	5-10 years	12	32.4%

3.2 AHP Method

The AHP method was developed by Saaty and is significant for its structured approach to decision-making and prioritization of factors based on their relative importance (Abdulvahitoglu and Kilic, 2022). It allows decision-makers to break down complex problems into smaller, more manageable parts, and to evaluate and compare different criteria or alternatives. Detailed procedures (Saaty, 1994; Bari et al., 2022) of the AHP method are as follows-

Step 1. Using the opinions of experts, generate pair-wise comparison matrices of the criteria as the following matrix.

$$C_{n\times n} = \begin{bmatrix} 1 & \tilde{c}_{12} & \tilde{c}_{13} & \cdots & \tilde{c}_{1n} \\ \tilde{c}_{12}{}^{-1} & 1 & \tilde{c}_{23} & \cdots & \tilde{c}_{2n} \\ \tilde{c}_{13}{}^{-1} & \tilde{c}_{23}{}^{-1} & 1 & \cdots & \tilde{c}_{3n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \tilde{c}_{1n}{}^{-1} & \tilde{c}_{2n}{}^{-1} & \tilde{c}_{3n}{}^{-1} & \cdots & 1 \end{bmatrix}$$

Step 2. The consistency of each pair-wise comparison matrix was confirmed by maintaining a Consistency Ratio of less than or equal to 0.1 following Equations (3.1) and (3.2).

$$CI = \frac{\lambda_{\max} - n}{n-1} \quad 3.1$$

$$CR = \frac{CI}{RI} \leq 0.1 \quad 3.2$$

Here, CI stands for consistency index, CR stands for consistency ratio and RI stands for random index. $\lambda_{\max}$ is the maximum eigenvalue of the matrix and represents the average weight of the criteria. In this study, n = 6, and RI = 1.24 for 6 criteria. If the CR is greater than 0.1, the decision-maker needs to revise the pairwise comparison matrix to improve its consistency.

Step 3. All of the pair-wise comparison matrices were combined into a single pair-wise comparison matrix using the geometric mean approach.

Step 4. The aggregated pair-wise matrix was normalized.

Step 5. The weights of the criteria were determined through the arithmetic mean of all the row elements of the aggregated pair-wise matrix.

3.3 TOPSIS Method

TOPSIS, developed by Hwang and Yoon, is a method for evaluating alternatives based on their similarity to the ideal solution (Hwang and Yoon, 1981; Mokhtar et al., 2015). This MCDM tool has gained popularity due to its simplicity, computational efficiency, and comprehensive mathematical concept (Menon and Ravi, 2022). TOPSIS is founded on two concepts, the positive and negative ideal solutions. Detailed procedures (Hwang and Yoon, 1981; Bari et al., 2022) of the TOPSIS method are as follows-

Step 1**.** Establishing the decision matrix where each element of the decision matrix (x_{ij}) is a measure of criterion C_j over alternative A_i.

Step 2. Creating the normalized decision matrix with Equation (3.3).

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^{m}(x_{ij})^2}}\ , i = 1, 2, 3, \ldots\ldots, m;\ j = 1, 2, \ldots\ldots, n \qquad 3.3$$

Step 3. Creating the weighted normalized decision matrix with Equation (3.4).

$$v_{ij} = w_j \times r_{ij}, i = 1, 2, \ldots\ldots, m;\ j = 1,2, \ldots\ldots, n \qquad 3.4$$

where w_j represents the weight of criterion j indicating its relative importance, compared to other criteria.

Step 4. Determining the positive and negative ideal solutions with Equations (3.5) and (3.6).

$$A^{+} = \{V_1{}^{+}, V_2{}^{+}, \ldots\ldots, V_j{}^{+}, \ldots\ldots, V_n{}^{+}\} = \{(\underset{\forall i}{max} V_{ij} | j\varepsilon J^{+}), (\underset{\forall i}{min} V_{ij} | j\varepsilon J^{-})\} \qquad 3.5$$

$$A^{-} = \{V_1{}^{-}, V_2{}^{-}, \ldots\ldots, V_j{}^{-}, \ldots\ldots, V_n{}^{-}\} = \{(\underset{\forall i}{min} V_{ij} | j\varepsilon J^{+}), (\underset{\forall i}{max} V_{ij} | j\varepsilon J^{-})\} \qquad 3.6$$

where A^{+} indicates the positive ideal solution, A^{-} represents the negative ideal solution, J^{+} is regarded as the set of positive criteria, and J^{-} displays the set of negative criteria.

Step 5. Calculating the distances from A^{+} and A^{-} with Equations (3.7) and (3.8).

$$s_i{}^{+} = \sqrt{\sum_{j=1}^{n}(V_{ij} - V_j{}^{+})^{2}} \qquad 3.7$$

$$s_i{}^{-} = \sqrt{\sum_{j=1}^{n}(V_{ij} - V_j{}^{-})^{2}} \qquad 3.8$$

Where $s_i{}^{+}$ indicates the distance from the positive ideal solution and $s_i{}^{-}$ shows the distance from the negative ideal solution.

Step 6. Calculating the similarity index and ranking alternatives with Equation (3.9).

$$c_i^{+} = \frac{s_i^{-}}{s_i^{+} + s_i^{-}}, 0 < c_i^{+} < 1 \quad 3.9$$

Alternatives are ranked based on the descending order of the similarity index (c_i^{+}) t

3.4 PROMETHEE Method

The PROMETHEE methodology is a useful tool for analyzing multi-criteria problems and determining priority order in decision-making. Like the TOPSIS, PROMETHEE is also a relatively simple ranking method in conception and application. PROMETHEE is particularly effective for ranking problems with a finite number of alternatives based on conflicting criteria (Ziemba and Gago, 2022). The method includes a partial ranking component (PROMETHEE I) and a complete ranking component (PROMETHEE II). In this study, PROMETHEE II is used for determining a complete ranking. Detailed procedures (Krouska et al., 2022) of the PROMETHEE II method are as follows-

Step 1. Establishing the decision matrix where each element of the decision matrix (xij) is a measure of criterion C_j over alternative A_i.

Step 2. Determining the deviation of the related alternatives for each criterion with Equation (3.10).

$$d_j(A_i, A_{i'}) = C_j(A_i) - C_j(A_{i'}), i = 1, 2, \dots, m; \; i' = 1, 2, \dots, m; \; j = 1, 2, \dots, n \quad 3.10$$

where d_j $(A_i, A_{i'})$ represents the difference between two evaluations $(A_i, A_{i'})$ on each criterion. This equation is inverted to a negative nature for the criterion.

Step 3. Calculating the preference function value with Equation (3.11).

$$P_j(A_i, A_{i'}) = f\,[\,d_j(A_i, A_{i'})\,] \quad 3.11$$

where f indicates the preference function which is determined based on the nature of each criterion and the decision maker's opinion.

Step 4. Calculating the preference index with Equation (3.12).

$$\pi\,(A_i\,, A_{i'}) = \sum_{j=1}^{n} P_j(A_i\,, A_{i'})w_j \quad , \quad \sum_{j=1}^{n} w_j = 1 \qquad 3.12$$

where w_j displays the relative weight of each criterion.

Step 5. Calculating the outranking flows with Equations (3.13) and (3.14).

$$Ø^{+}(A_i) \;=\; \frac{1}{m-1}\textstyle\sum_{x\,\varepsilon A} \pi\,(A_i\,, A_{i'}) \qquad 3.13$$

$$Ø^{-}(A_i) \;=\; \frac{1}{m-1}\sum_{x\,\varepsilon A} \pi\,(A_i\,, A_{i'}) \qquad 3.14$$

where $Ø^{+}(A_i)$, and $Ø^{-}(A_i)$ are described as the leaving and entering flow, respectively.

Step 6. Calculating the net outranking flow Equation (3.15).

$$Ø\,(A_i) = Ø^{+}(A_i) - Ø^{-}(A_i) \qquad 3.15$$

Alternatives are ranked based on the descending order of the outranking flow.

Chapter -4 Data Collection and Analysis

4.1. Identifying the Risk Prioritizing Criteria

Criteria selection is a crucial step in prioritizing alternatives in a hybrid MCDM technique, as the weights assigned to each criterion heavily influence the final ranking score. It is also important that the chosen criteria are relevant to the study objective, selected risk factors, and study scope (Bari et al., 2022). After a thorough review of the literature, this study scrutinized six risk-prioritizing criteria to assess the risk factors in the subsequent phase of the study. Furthermore, these criteria were validated by experts using a 'yes' or 'no' based response. A detailed description of the selected criteria for prioritizing LPG supply chain risks can be found in Table 4.1.

Table 4.1. LPG supply chain risk prioritization criteria

Criteria	Description of the criteria	Source
Probability of occurrence **(C1)**	Determine the likelihood of each risk factor occurring based on historical data, industry trends, and other relevant information.	Abdel-Basset et al. (2019); Junaid et al. (2019)
Impact on business **(C2)**	Assess the potential impact of each risk factor on the business considering revenue, market share, customer satisfaction, brand reputation, operational disruptions, and potential legal liabilities.	Ali et al. (2019); Abdel-Basset and Mohamed (2020)
The difficulty of mitigation **(C3)**	Evaluate the difficulty of mitigating each risk factor considering the availability of alternative suppliers, the cost of implementing risk mitigation measures, and the complexity of implementing those measures.	Ali et al. (2019); Rathore et al. (2021)
Time sensitivity **(C4)**	Consider the time-sensitivity of each risk factor. Some risks may have immediate consequences, while others may have a longer-term impact	Yazdani et al. (2021)
Supplier criticality **(C5)**	Consider the criticality of each supplier to the business operations based on the level of dependency on the supplier, the volume of goods or services supplied, and the availability of alternative suppliers.	Paksoy et al. (2019); Mari et al. (2019)
Geographic location **(C6)**	Assess the risks associated with the geographic location of the suppliers, including political instability, natural disasters, and transportation infrastructure.	Golan et al. (2020); Piprani et al. (2020)

4.2. Identifying the Risk Factors

Supply chain risk factors are events, situations, or circumstances that can impact the performance and stability of a supply chain. These risk factors can arise at any stage of the supply chain, from the procurement of raw materials to the delivery of finished products to customers (Ali et al., 2019). Managing these risk factors is essential for ensuring the efficiency, resilience, and sustainability of supply chains (Moktadir et al., 2018). After conducting a comprehensive literature review, this study enlisted 17 risk factors related to supply chain resilience in the context of global political crises and the post-pandemic era. Given the lack of research on the identification of LPG supply chain risk factors, the study also reviewed literature from other related sectors. The search strings for scholarly articles included ("LPG" OR "supply chain") AND ("risk" OR "risk factor"), "supply chain" AND ("COVID-19" OR "war"), and so on. These risk factors were subsequently modified and validated by experts using a 'yes' or 'no' based response. A detailed description of the selected risk factors for the LPG supply chain can be found in Table 4.2.

Table 4.2. Identified risk factors for the LPG supply chain.

Codes	Risk Factors	Description	Source
R1	Supply disruption due to natural or man-made disasters such as pandemics or war	Natural disasters include earthquakes, hurricanes, floods, and fires, which can damage LPG storage facilities, pipelines, and transportation systems, making it difficult or impossible to deliver LPG to the end users. Man-made disasters such as pandemics or wars can also disrupt the supply of LPG by restricting the movement of people and goods, closing borders, and imposing trade barriers, which can cause shortages and price fluctuations in the market.	Allam et al. (2022); Andiappan et al. (2021)
R2	Price fluctuations due to changes in demand or supply, geopolitical events, or regulatory changes	Price fluctuations refer to the changes in the market price of a product or commodity over time. In the case of LPG, price fluctuations can be caused by various factors, including changes in demand or supply, geopolitical events, or regulatory changes. For example, an increase in demand for LPG during winter months when people use more heating can lead to a rise in its price. Similarly, supply disruptions due to natural disasters or geopolitical events can also cause price fluctuations. Regulatory changes, such as	Althaf and Babbitt (2021); Michail and Melas (2022)

Codes	Risk Factors	Description	Source
		taxes or tariffs, can also impact the price of LPG.	
R3	Equipment failures during production, storage, or transportation	Equipment failures during the production, storage, or transportation of LPG refer to any malfunction, damage, or breakdown of equipment that is used in the processes of producing, storing, or transporting LPG. This can include issues with pipelines, valves, tanks, pumps, compressors, or other equipment used in LPG facilities or transport vehicles. Equipment failures can cause safety hazards, such as gas leaks or fires, and can result in significant economic losses due to delays or interruptions in the supply chain.	Gallab et al. (2017); Bariha et al. (2023)
R4	Cybersecurity breaches including hacking, malware, and other types of cyber-attacks	In today's digitalized era, companies operating in the LPG supply chain are increasingly reliant on technology, including computer networks and software systems, to manage their operations. This reliance on technology exposes the industry to the risk of cybersecurity breaches, which include hacking, malware, and other types of cyber-attacks. A successful cyber-attack can compromise the confidentiality, integrity, or availability of sensitive information and critical systems, leading to financial losses, reputational damage, and even physical harm.	Ghadge et al. (2020); Ahmed et al. (2023)
R5	Regulatory compliance failures to comply with environmental, health, and safety regulations	The risk of regulatory compliance failure in the LPG supply chain refers to the possibility of not being able to comply with environmental, health, and safety regulations set by regulatory bodies. These regulations are put in place to ensure the safety of people, the environment, and the products themselves. Non-compliance can result in legal action, fines, or even the closure of the business, which can significantly impact the LPG supply chain. Factors that can contribute to non-compliance include inadequate monitoring, ineffective training of personnel, lack of awareness, and human error.	Ganesh et al. (2022); Menon and Ravi (2022)
R6	Capacity constraints including inadequate inventory or transportation infrastructure	Capacity constraints could arise if there is a shortage of storage facilities, pipelines, or transport vehicles to move LPG to different locations. If demand for LPG increases while the supply chain's capacity remains the same, this could result in supply shortages and price increases. In addition, inadequate transportation infrastructure, such as poor road	Moktadir et al. (2018); Shih (2020)

Codes	Risk Factors	Description	Source
		conditions, can delay the delivery of LPG and disrupt the supply chain.	
R7	Political instability or unrest in key supplier or consumer markets	Political instability or unrest in key supplier or consumer markets can disrupt the LPG supply chain. For example, if a country that supplies LPG experiences political unrest, it could lead to a disruption in the production and supply of LPG. Similarly, if a country that consumes a significant amount of LPG experiences political instability, it could lead to a decrease in demand, which could affect the market price of LPG. Political instability can also lead to changes in regulations, tariffs, or trade policies, which can affect the import or export of LPG.	Norouzi (2021); Emenike and Falcone (2020)
R8	Shortage of skilled labor or technical expertise to manage the supply chain	The shortage of skilled labor or technical expertise refers to a situation where there is a lack of skilled workers or professionals who are knowledgeable and experienced in managing various aspects of the LPG supply chain. This can include expertise in areas such as production, logistics, distribution, storage, and safety. When there is a shortage of such skilled labor or technical expertise, it can lead to inefficiencies, errors, and delays in the supply chain, which can ultimately impact the availability and cost of LPG for end consumers.	Moktadir et al. (2018); Ali et al. (2019)
R9	Quality issues including contamination or adulteration of LPG during production or transportation	Contamination or adulteration can occur due to various reasons, such as poor handling practices, inadequate storage facilities, or equipment failure during transportation. Contamination or adulteration can affect the quality and purity of LPG, leading to safety risks, customer complaints, and reputational damage for the company. Moreover, the quality of LPG must meet regulatory and safety standards, and any failure to comply with these standards can result in legal penalties or fines.	Um and Han (2021); Nayal et al. (2022)
R10	Theft, pilferage, or hijacking of LPG cargo during transportation	The transportation of LPG involves the movement of large volumes of valuable and flammable cargo through various transportation modes such as trucks, and ships. This makes it an attractive target for theft, pilferage, or hijacking, which can result in significant financial losses for the supply chain. Criminals may steal the LPG by breaking into the storage tanks or by hijacking	Alfaqiri et al. (2019)

Codes	Risk Factors	Description	Source
		the vehicles, causing a delay in the delivery of the cargo.	
R11	Dependence on a small number of suppliers or buyers	Dependence on a small number of suppliers or buyers can lead to a lack of diversification and an overreliance on a single supplier or buyer. If the supplier or buyer experiences disruptions, such as production delays, quality issues, or market fluctuations, it can negatively impact the entire supply chain. Moreover, the supplier or buyer may also have significant bargaining power, which can result in unfavorable terms for the other parties in the supply chain, leading to lower profits and operational inefficiencies.	Silvestre et al. (2020); Wissuwa et al. (2022)
R12	Market competition leading to price wars or lower margins	When there are many suppliers competing for a limited number of buyers, there can be downward pressure on prices, which can lead to lower profit margins. This can result in suppliers cutting costs by reducing quality, safety, or environmental standards, which can increase the risk of accidents or environmental damage. Lower margins may also make it difficult for suppliers to invest in the research and development of new technologies, making it harder for them to remain competitive in the long term. Price wars may also lead to an overcapacity of supply, which can result in excess inventory and storage issues.	Sodhi and Tang (2021); Duong et al. (2022)
R13	Insufficient monitoring or tracking of LPG supply chain activities	Insufficient monitoring can lead to a lack of visibility into the flow of products and information, making it difficult to identify and address issues that may arise. This can result in delays, disruptions, and losses in the supply chain, including theft or loss of cargo, non-compliance with regulations, quality issues, and other risks. Without adequate monitoring and tracking, it may also be challenging to maintain a secure and efficient supply chain and to make informed decisions on inventory management, transportation, and other key aspects of supply chain operations.	Alam et al. (2021); Ahmed et al. (2023)
R14	Changes in consumer preferences or behavior including a shift towards other energy sources	If consumers shift towards other energy sources such as natural gas or renewable energy, the demand for LPG may decrease. This can lead to excess inventory, reduced production, and lower profits for LPG suppliers. Additionally, changes in consumer preferences for LPG products, such as	Taghikhah et al. (2019); Modgil et al. (2022)

Codes	Risk Factors	Description	Source
		preferring smaller or larger gas canisters, can also impact the supply chain.	
R15	Adverse weather conditions including extreme heat or cold impacting transportation and storage	Extreme heat can cause the pressure in LPG tanks to rise, potentially leading to equipment failures or explosions, while extreme cold can cause the LPG to lose pressure, leading to reduced efficiency and potentially affecting the overall quality of the fuel. Additionally, severe weather events like hurricanes or floods can disrupt transportation routes, cause delays, and damage storage facilities, which can impact the supply and availability of LPG.	Emenike and Falcone (2020)
R16	Economic or financial crises leading to changes in demand and supply	An economic or financial crisis, such as a recession or market downturn, can have significant impacts on the demand and supply of LPG, leading to risks for the LPG supply chain. During such crises, demand for LPG may decrease due to reduced economic activity and lower consumer spending, which can result in excess inventory and supply chain disruptions. On the other hand, supply may be impacted by factors such as reduced investment and production capacity, leading to shortages and price fluctuations. These economic and financial risks can also impact the financial stability of companies involved in the LPG supply chain, leading to increased debt, bankruptcy, and other financial issues.	Yu et al. (2021); Duong et al. (2022)
R17	Supply disruptions due to labor strikes, protests, or other forms of civil unrest	Such disruptions can occur when workers or other groups protest against certain policies or working conditions. The disruption can cause delays in the production, transportation, or delivery of LPG, leading to a shortage of supply. The risk is particularly high when the supply chain is dependent on a few suppliers or transportation routes.	Handfield et al. (2020)

4.3. Collecting and Analyzing Experts' Evaluation for the Criteria and the Risk Factors

The study utilized a two-phase evaluation process to collect expert opinions and evaluate criteria and risk factors. The first phase involved a semi-structured survey questionnaire to evaluate the criteria, while the second phase involved another semi-structured survey questionnaire to evaluate the risk factors. The evaluation score from the first phase was then used in the AHP method to determine the criteria weights, while the evaluation score from the second phase was used in both AHP-TOPSIS and AHP-PROMETHEE methods to determine the final ranking of the risk factors. The survey questionnaire was created in Google Forms and distributed to the experts through email communication. A sample of the survey questionnaires used in the two phases can be found in Appendix A, Table A1 and Table A2.

For collecting experts' opinions, this study utilized a 9-point evaluation scale in both phases of survey response collection. That scale was introduced by Saaty (1977). Table 4.3 is showing the 9-point scale.

Table 4.3. A 9-point evaluation scale for collecting experts' opinion.

Linguistic variables	Numeric values
Equal	1
Between equal and moderate	2
Moderate	3
Between moderate and strong	4
Strong	5
Between strong and very strong	6
Very strong	7
Between very strong and extremely strong	8
Extremely strong	9

4.3.1. Criteria Weights

A sample pair-wise matrix formed with the response from an expert for the AHP method can be found in Appendix B, Table B1. The consistency ratio for that response was 0.015, which is less than 0.1 and acceptable. Similar 17 responses collected from 37 experts were aggregated to form the aggregated pair-wise matrix shown in Table 4.4.

Table 4.4. Aggregated pair-wise comparison matrix for the criteria

	C1	C2	C3	C4	C5	C6
C1	1.00	0.92	5.80	3.87	2.86	5.80
C2	1.08	1.00	6.16	4.15	3.10	6.25
C3	0.17	0.16	1.00	0.51	0.49	1.00
C4	0.26	0.24	1.97	1.00	0.92	1.92
C5	0.35	0.32	2.05	1.08	1.00	2.00
C6	0.17	0.16	1.00	0.52	0.50	1.00

The consistency ratio for this aggregated pair-wise comparison matrix was 0.00167, which is less than 0.1 and acceptable. The normalized matrix is shown in Table 4.5.

Table 4.5. Normalized pair-wise comparison matrix for the criteria

	C1	C2	C3	C4	C5	C6
C1	0.33	0.33	0.32	0.35	0.32	0.32
C2	0.36	0.36	0.34	0.37	0.35	0.35
C3	0.06	0.06	0.06	0.05	0.06	0.06
C4	0.09	0.09	0.11	0.09	0.10	0.11
C5	0.12	0.11	0.11	0.10	0.11	0.11
C6	0.06	0.06	0.06	0.05	0.06	0.06

The obtained weights of the criteria from the normalized matrix are shown in Table 4.6.

Table 4.6. Obtained criteria weights.

Criteria	Weights
Probability of occurrence (C1)	0.329
Impact on business (C2)	0.354
The difficulty of mitigation (C3)	0.054
Time sensitivity (C4)	0.097
Supplier criticality (C5)	0.111
Geographic location (C6)	0.055

4.3.2. Risk Ranking

A sample decision matrix formed with the response from an expert for the AHP-TOPSIS and the AHP-PROMETHEE method can be found in Appendix B, Table B2. Similar 17 responses collected from 37 experts were aggregated to form the aggregated decision matrix which is shown in Table 4.7.

Table 4.7. Aggregated decision matrix with the experts' evaluation scores

Denotations	C1	C2	C3	C4	C5	C6
R1	4.05	6.94	6.94	5.05	6.05	7.94
R2	5.15	7.94	5.10	7.94	4.15	5.05
R3	5.05	4.93	3.05	5.94	1.04	1.92
R4	4.90	7.94	7.94	8.94	4.93	2.05
R5	3.05	7.94	6.05	8.94	3.93	4.93
R6	2.05	3.93	2.05	6.94	5.05	1.04
R7	3.05	4.93	5.94	6.94	4.05	3.93
R8	3.05	3.93	3.05	3.05	2.93	3.05
R9	1.04	7.94	3.05	6.94	2.05	1.04

Denotations	C1	C2	C3	C4	C5	C6
R10	1.04	3.93	1.04	1.04	2.05	3.05
R11	3.05	5.94	4.05	3.05	7.94	2.05
R12	2.05	4.93	6.05	5.05	2.05	1.04
R13	2.05	5.94	2.05	6.05	2.05	2.05
R14	1.04	4.05	7.94	7.94	5.94	3.05
R15	1.04	1.04	5.05	5.05	3.05	6.94
R16	4.05	6.94	7.06	7.94	6.94	5.94
R17	2.05	5.05	5.94	7.94	6.05	3.05

The normalized matrix obtained from the aggregated decision matrix is shown in Table 4.8.

Table 4.8. Normalized decision matrix

Denotations	C1	C2	C3	C4	C5	C6
R1	0.085	0.074	0.084	0.048	0.086	0.137
R2	0.108	0.084	0.062	0.076	0.059	0.087
R3	0.106	0.052	0.037	0.057	0.015	0.033
R4	0.103	0.084	0.096	0.085	0.070	0.035
R5	0.064	0.084	0.074	0.085	0.056	0.085
R6	0.043	0.042	0.025	0.066	0.072	0.018
R7	0.064	0.052	0.072	0.066	0.058	0.068
R8	0.064	0.042	0.037	0.029	0.042	0.052
R9	0.022	0.084	0.037	0.066	0.029	0.018
R10	0.022	0.042	0.013	0.010	0.029	0.052
R11	0.064	0.063	0.049	0.029	0.113	0.035
R12	0.043	0.052	0.074	0.048	0.029	0.018
R13	0.043	0.063	0.025	0.058	0.029	0.035
R14	0.022	0.043	0.096	0.076	0.084	0.052
R15	0.022	0.011	0.061	0.048	0.043	0.119
R16	0.085	0.074	0.086	0.076	0.099	0.102
R17	0.043	0.054	0.072	0.076	0.086	0.052

The calculated ranking of the risk factors by the AHP-TOPSIS can be found in Table 4.9.

Table 4.9. Ranking of the risk factors by the AHP-TOPSIS method

Denotations	C1	C2	C3	C4	C5	C6	s_i^+	s_i^-	c_i^+	Rank
R1	0.028	0.026	0.005	0.005	0.010	0.007	0.010	0.032	0.770	**4**
R2	0.035	0.030	0.003	0.007	0.007	0.005	0.007	0.039	0.851	**1**
R3	0.035	0.019	0.002	0.005	0.002	0.002	0.017	0.032	0.647	**6**

Denotations	C1	C2	C3	C4	C5	C6	s_i^+	s_i^-	c_i^+	Rank
R4	0.034	0.030	0.005	0.008	0.008	0.002	0.007	0.039	0.837	**2**
R5	0.021	0.030	0.004	0.008	0.006	0.005	0.016	0.031	0.658	**5**
R6	0.014	0.015	0.001	0.006	0.008	0.001	0.028	0.015	0.357	**14**
R7	0.021	0.019	0.004	0.006	0.006	0.004	0.020	0.022	0.524	**8**
R8	0.021	0.015	0.002	0.003	0.005	0.003	0.024	0.018	0.433	**12**
R9	0.007	0.030	0.002	0.006	0.003	0.001	0.031	0.027	0.464	**9**
R10	0.007	0.015	0.001	0.001	0.003	0.003	0.035	0.011	0.243	**16**
R11	0.021	0.022	0.003	0.003	0.013	0.002	0.018	0.026	0.584	**7**
R12	0.014	0.019	0.004	0.005	0.003	0.001	0.027	0.017	0.387	**13**
R13	0.014	0.022	0.001	0.006	0.003	0.002	0.026	0.020	0.443	**11**
R14	0.007	0.015	0.005	0.007	0.009	0.003	0.032	0.016	0.330	**15**
R15	0.007	0.004	0.003	0.005	0.005	0.007	0.039	0.008	0.166	**17**
R16	0.028	0.026	0.005	0.007	0.011	0.006	0.009	0.033	0.788	**3**
R17	0.014	0.019	0.004	0.007	0.010	0.003	0.025	0.020	0.446	**10**

The preference function for the AHP-PROMETHEE method can be found in Table 4.10.

Table 4.10. Preference function

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17
R1		0.007	0.024	0.007	0.014	0.036	0.022	0.032	0.036	0.051	0.020	0.035	0.033	0.036	0.050	0.002	0.026
R2	0.014		0.023	0.005	0.015	0.043	0.028	0.039	0.038	0.058	0.030	0.042	0.039	0.045	0.059	0.011	0.034
R3	0.008	0.000		0.001	0.014	0.026	0.014	0.020	0.028	0.037	0.016	0.022	0.021	0.031	0.043	0.007	0.021
R4	0.014	0.004	0.024		0.016	0.041	0.029	0.040	0.037	0.058	0.028	0.041	0.038	0.042	0.061	0.011	0.033
R5	0.007	0.002	0.023	0.003		0.030	0.014	0.026	0.024	0.044	0.017	0.028	0.025	0.031	0.045	0.005	0.021
R6	0.002	0.001	0.007	0.000	0.002		0.002	0.007	0.012	0.018	0.004	0.006	0.006	0.007	0.023	0.000	0.000
R7	0.002	0.001	0.009	0.002	0.000	0.016		0.012	0.022	0.030	0.007	0.015	0.015	0.018	0.032	0.000	0.008
R8	0.000	0.000	0.004	0.001	0.000	0.009	0.000		0.017	0.018	0.001	0.010	0.010	0.014	0.025	0.000	0.007
R9	0.006	0.000	0.014	0.000	0.000	0.016	0.011	0.019		0.022	0.011	0.013	0.009	0.015	0.028	0.004	0.011
R10	0.000	0.000	0.003	0.001	0.000	0.002	0.000	0.000	0.002		0.001	0.002	0.001	0.000	0.011	0.000	0.000
R11	0.003	0.006	0.015	0.005	0.006	0.021	0.010	0.016	0.025	0.035		0.021	0.018	0.024	0.040	0.002	0.013
R12	0.000	0.001	0.004	0.000	0.000	0.006	0.000	0.008	0.009	0.018	0.003		0.003	0.010	0.022	0.000	0.000
R13	0.001	0.000	0.006	0.000	0.000	0.008	0.004	0.010	0.008	0.020	0.003	0.006		0.014	0.026	0.000	0.003
R14	0.003	0.005	0.014	0.003	0.004	0.009	0.005	0.013	0.012	0.018	0.008	0.012	0.013		0.020	0.001	0.001

	R1	**R2**	**R3**	**R4**	**R5**	**R6**	**R7**	**R8**	**R9**	**R10**	**R11**	**R12**	**R13**	**R14**	**R15**	**R16**	**R17**
R15	0.000	0.002	0.009	0.005	0.002	0.008	0.003	0.007	0.008	0.012	0.007	0.007	0.008	0.004		0.001	0.004
R16	0.004	0.007	0.025	0.007	0.013	0.037	0.023	0.034	0.037	0.053	0.021	0.037	0.034	0.036	0.053		0.026
R17	0.003	0.004	0.013	0.003	0.003	0.011	0.005	0.016	0.018	0.027	0.007	0.011	0.012	0.011	0.030	0.000	

The calculated ranking of the risk factors by the AHP-PROMETHEE II can be found in Table 4.11.

Table 4.11. Ranking of the risk factors by the AHP- PROMETHEE II method

Risks	Leaving flow	Entering flow	Net outranking flow	Rank
R1	0.027	0.004	0.023	**4**
R2	0.033	0.002	0.030	**1**
R3	0.019	0.014	0.006	**6**
R4	0.032	0.003	0.030	**2**
R5	0.022	0.006	0.016	**5**
R6	0.006	0.020	-0.014	**14**
R7	0.012	0.011	0.001	**8**
R8	0.007	0.019	-0.011	**12**
R9	0.011	0.021	-0.010	**10**
R10	0.001	0.032	-0.031	**17**
R11	0.016	0.011	0.005	**7**
R12	0.005	0.019	-0.014	**15**
R13	0.007	0.018	-0.011	**11**
R14	0.009	0.021	-0.012	**13**
R15	0.005	0.036	-0.030	**16**
R16	0.028	0.003	0.025	**3**
R17	0.011	0.013	-0.002	**9**

Chapter -5 Results and Discussions

5.1. Results

The obtained weights of the criteria (see Table 4.5) are as C2 (0.354) > C1 (0.329) > C5 (0.111) > C4 (0.097) > C6 (0.055) > C3 (0.054). Figure 5.1 is depicting the weights of the criteria.

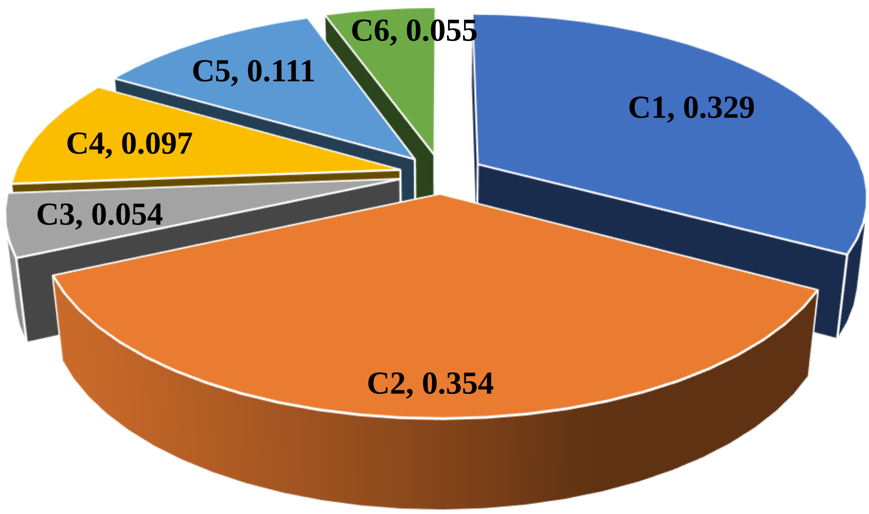

Figure 5.1. Weights of the criteria

The obtained ranking of the risks by the AHP-TOPSIS method (see Table 4.8) is as R2 > R4 > R16 > R1 > R5 > R3 > R11 > R7 > R9 > R17 > R13 > R8 > R12 > R6 > R14 > R10 > R15. Figure 5.2 is depicting the results obtained by the AHP-TOPSIS method.

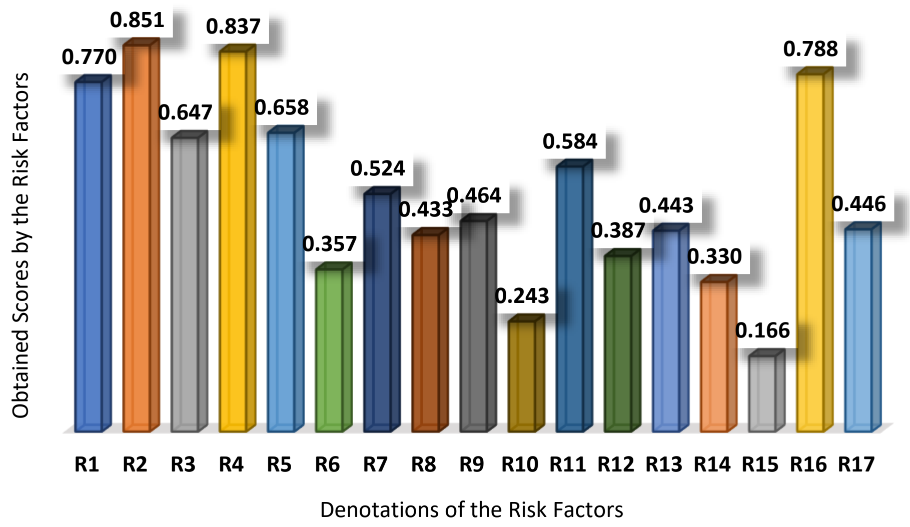

Figure 5.2. Ranking of the risks obtained by the AHP-TOPSIS

The obtained ranking of the risks by the AHP-PROMETHEE II method (see Table 3.16) is as R2 > R4 > R16 > R1 > R5 > R3 > R11 > R7 > R17 > R9 > R13 > R8 > R14 > R6 > R12 > R15 > R10. Figure 5.3 is depicting the results obtained by the AHP-PROMETHEE II method.

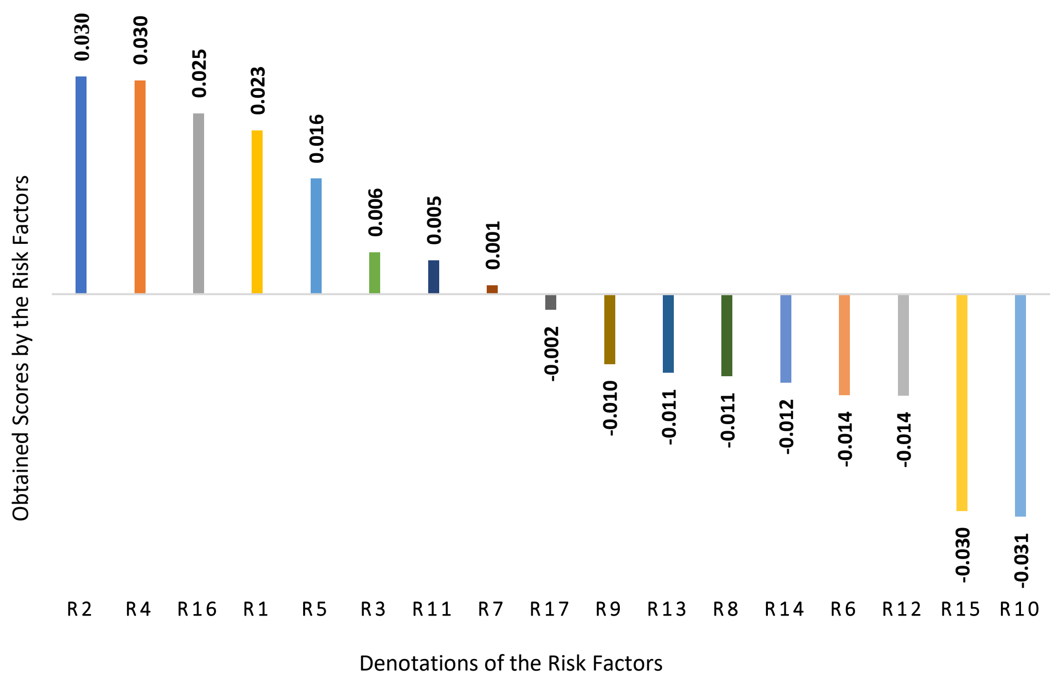

Figure 5.3. Ranking of the risks obtained by the AHP-PROMETHEE II

A comparison of the obtained ranking from two distinct phases of this study is shown in Table 5.1 and Figure 5.4.

Table 5.1 Comparison rankings in two methods

Risks	AHP-TOPSIS	AHP-PROMETHEE II
R1	4	4
R2	1	1
R3	6	6
R4	2	2
R5	5	5
R6	14	14
R7	8	8
R8	12	12
R9	9	10
R10	16	17
R11	7	7
R12	13	15
R13	11	11
R14	15	13
R15	17	16
R16	3	3
R17	10	9

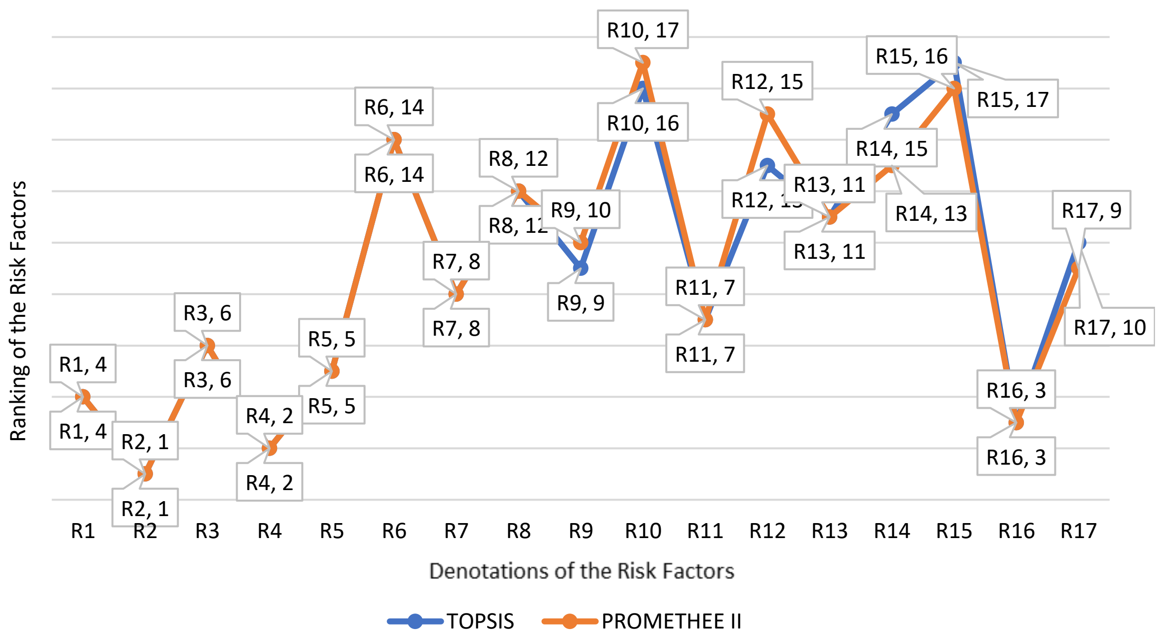

Figure 5.4. A comparison between rankings of TOPSIS and PROMETHEE II

5.2. Discussions

5.2.1. Criteria Weights

The AHP has determined 'Impact on business (C2)' as the most important criterion for prioritizing supply chain risk factors, as it directly affects the organization's bottom line. Risks that have a higher potential impact on critical business objectives, such as revenue, profitability, and customer satisfaction, should be given the highest priority (Abdel-Basset and Mohamed, 2020). Risks that could have severe financial, operational, or reputational consequences, should be given high priority, even if they have a lower probability of occurrence. The 'Probability of occurrence (C1)' of a risk factor is determined as the second most weighted criterion in this study. This should also be taken into account, especially when considering the likelihood of a specific risk happening. Risks with a higher probability of occurrence should be given more priority than risks that are less likely to occur (Junaid et al., 2019).

The third most weighted criterion 'Supplier criticality (C5)' of each supplier to the business operations should also be considered. Suppliers that are more critical or essential to the business, such as those who supply essential components or provide unique services, should be given high priority (Mari et al., 2019). Therefore, the risk factors that are highly scored in this criterion can get an overall high prioritization score, thus ranking in the top position. 'Time sensitivity (C4)' of a risk factor is the fourth weighted criterion according to the study result that should also be considered. Risks that could have an immediate impact on the business should be given higher priority than risks that could have a longer-term impact (Yazdani et al., 2021).

'The difficulty of mitigation (C3)' and 'Geographic location (C6)' are also important criteria, however, this study weighted these two criteria comparatively less than the other criteria. The difficulty of mitigating a risk factor should be considered, as it affects the organization's ability to manage the risk. Risks that are more difficult to mitigate should be given more priority than risks that can be easily mitigated. Similarly, risks associated with volatile regions should be given some priority. However, when the risks associated with the topmost weighted criteria are addressed, that will consequently mitigate the risks associated with the low-weighted criteria (Ali et al., 2019).

5.2.2. Risk Ranking

This study determined the topmost risks consistent for both ranking methods applied in the research, which is ensuring the sensitivity of the obtained result (see Table 4.2 and Figure 4.5). Only a little difference is observed for some of the lower-ranked risks in the two methods. For example, both of the rankings showed, ‘Price fluctuations due to changes in demand or supply, geopolitical events, or regulatory changes (R2)’, ‘Cybersecurity breaches including hacking, malware, and other types of cyber-attacks (R4)’, ‘Economic or financial crises leading to changes in demand and supply (R16)’, ‘Supply disruption due to natural or man-made disasters such as pandemics or war (R1)’, and ‘Regulatory compliance failures to comply with environmental, health and safety regulations (R5)’ are the topmost prioritized five risk factors for the local and global supply chain of LPG.

Price fluctuations due to changes in demand or supply, geopolitical events, or regulatory changes are the topmost prioritized risk factors in the LPG supply chain of Bangladesh and the international supply chain because they can significantly impact the profitability and sustainability of the LPG industry. Changes in demand or supply, geopolitical events, or regulatory changes can cause sudden and unexpected shifts in market conditions, leading to price fluctuations. For example, a sudden increase in demand due to a severe winter or a sudden decrease in supply due to unforeseen production disruptions can cause prices to rise.

Similarly, geopolitical events such as political instability, conflicts, or sanctions can cause disruptions in the supply chain and lead to price fluctuations (Michail and Melas, 2022). Regulatory changes can also have a significant impact on LPG prices. Changes in import or export regulations, taxes, or environmental regulations can affect the cost of production, transportation, and storage of LPG, which can ultimately affect its price. For example, if a government imposes a new tax on LPG imports, the cost of importing LPG will increase, leading to higher prices for consumers. Price fluctuations can also affect the entire supply chain, including producers, distributors, and retailers. For example, if the price of LPG suddenly increases, distributors and retailers may be unable to pass on the full cost to consumers, leading to reduced profit margins and potentially forcing them out of business. Therefore, this risk factor has significant economic consequences for all stakeholders involved in the LPG industry.

Cybersecurity breaches, including hacking, malware, and other types of cyber-attacks, are the second most prioritized risk factors in the LPG supply chain of Bangladesh, as well as for the international supply chain because they can have severe consequences for the industry's safety, security, and operations. Supply chain activities are shifting towards AI-based systems (Ahmed et al., 2023). LPG supply chain operations involve various critical information systems, such as SCADA (Supervisory Control and Data Acquisition) systems, distribution management systems, and logistics management systems. These systems are interconnected, and any vulnerability in one system can lead to a breach in the entire network. If cyber attackers gain unauthorized access to these systems, they can disrupt the entire supply chain's operations, leading to loss of production, reduced efficiency, and safety hazards.

Moreover, cyber attackers can target the LPG supply chain's critical infrastructure, such as storage terminals, refineries, and transportation infrastructure. A successful cyber-attack on these facilities can result in explosions, fires, and other safety incidents, causing significant loss of life and property damage. In addition to safety and security concerns, cyber-attacks can also impact the LPG industry's reputation and financial stability. A successful cyber-attack can lead to a loss of customer trust, reduced sales, and revenue loss. Companies may also face legal and regulatory consequences, leading to hefty fines and legal expenses. Therefore, cybersecurity breaches are considered a significant risk factor in the LPG supply chain of Bangladesh and the international supply chain, and it is crucial to implement robust cybersecurity measures to protect critical information systems and infrastructure from cyber-attacks.

Economic or financial crises can have a range of effects on the LPG supply chain, therefore this risk factor has been determined as the third most prioritized risk factor in this study. In times of economic downturn, businesses and consumers may reduce their energy consumption, leading to a decrease in demand for LPG (Cui et al., 2023). This can have a direct impact on LPG prices and volumes, which can affect the profitability and sustainability of LPG companies. Additionally, supply disruptions may occur during financial crises, as LPG producers and distributors face financial difficulties or operational challenges, such as a shortage of skilled labor or difficulty accessing capital. These supply disruptions can lead to increased volatility in LPG prices, supply shortages, and logistical challenges for LPG companies.

Supply disruptions due to natural or man-made disasters, such as pandemics or wars, are a significant risk factor in the LPG supply chain, thus ranked the fourth position in this study. These events can have a range of impacts on the LPG supply chain, including disruptions to transportation, production, and distribution systems, as well as a decrease in demand due to changes in consumer behavior (Allam et al., 2022). For example, pandemics can lead to workforce shortages and supply chain disruptions, while wars can result in damage to infrastructure, transportation disruptions, and increased security risks. In the case of LPG, supply disruptions due to natural or man-made disasters can have a significant impact on the availability and price of LPG, as well as the profitability and sustainability of LPG companies. For example, a natural disaster such as a hurricane or earthquake could damage LPG storage and transportation infrastructure, leading to supply shortages and price increases. Similarly, a pandemic could lead to a decrease in demand for LPG due to changes in consumer behavior, such as reduced travel or remote work, which could affect the financial performance of LPG companies.

Regulatory compliance failures are the fifth most significant risk factor in the LPG supply chain of Bangladesh and the international supply chain, as non-compliance with environmental, health, and safety regulations can result in legal, financial, and reputational risks. LPG companies must comply with a range of regulations, including those related to the production, transportation, storage, and distribution of LPG, as well as those related to environmental protection, workplace safety, and public health (Menon and Ravi, 2022).

Failure to comply with these regulations can result in fines, legal action, and reputational damage, as well as operational disruptions and reduced profitability. For example, a company may face fines or legal action if it violates safety regulations and causes an accident that harms workers or the public. Additionally, non-compliance with environmental regulations can result in damage to ecosystems and public health, leading to reputational damage and decreased demand for LPG products.

Other risk factors are also significant for the LPG supply chain. However, they are positioned comparatively lower as mitigating the topmost risk factors and consequently mitigating the other risk factors simultaneously (Moktadir et al., 2018). This stratified framework is the most important outcome of this research work.

5.3. Validation of the Results

The comparison between the two methods shows a little difference in the position for some of the lower-ranked risk factors. However, this is not significant from the perspective of overall study results. The discrepancy occurred only for the calculation techniques of the two MCDM methods, the TOPSIS and the PROMETHEE II.

The obtained study result is significantly unique in contrast to the previous studies on supply chain management in various other fields mentioned earlier in this study. For example, Michail and Melas (2022) described the supply disruptions issues due to price fluctuations. However, this ongoing study has determined that issue as the most prioritized risk factor in this ongoing war and post-pandemic era, which makes this study result unique. Similarly, Ahmed et al. (2023) and Klöckner et al. (2022) both studies emphasized the importance of incorporating digital technologies in the supply chain mechanisms to be more resilience in this global crisis scenario. However, those studies did not mention cyber security risk as one of the topmost prioritized risk factors in this era of digitalization, which is determined in this ongoing study. This uniqueness occurred due to the pattern and the framework of this research, as well as with the study context of the ongoing world political crisis and pandemic. As those studies were not aimed to conduct risk assessments of the LPG supply chain, they could not be directly relevant to analyze the risks of the LPG supply chain in the ongoing global context. However, those studies were important to design this research methodology and find a unique framework for this study.

5.4. Managerial and Policy Implications

Managers and policymakers can find significant insights from this study result. They can plan for a hierarchy of mitigation actions according to the obtained result of the study. For example, to mitigate the risk of price fluctuations due to changes in demand or supply, geopolitical events, or regulatory changes in the LPG supply chain, companies can diversify supply sources, negotiate flexible supply contracts, maintain strategic inventories, invest in market intelligence and forecasting, ensure regulatory compliance, collaborate with stakeholders, and develop comprehensive risk management strategies. These strategies can help companies ensure a steady supply of LPG, anticipate changes in market conditions, and minimize the impact of price fluctuations on their operations, thereby ensuring sustainable and profitable operations.

To mitigate the risk of cybersecurity breaches, LPG companies can develop and implement cybersecurity policies and procedures, conduct regular security assessments, provide employee training and awareness, implement advanced security technologies, develop an incident response plan, establish third-party risk management processes, and ensure compliance with industry standards. These strategies can help protect critical information systems, prevent disruption of operations, and safeguard against financial and reputational damage due to cyber-attacks in the LPG supply chain.

To mitigate the risk of economic or financial crises in the LPG supply chain, companies can adopt a range of strategies. For example, they can diversify their customer base and supply sources to minimize the impact of changes in demand or supply in a particular market or region. They can also invest in market intelligence and forecasting capabilities to anticipate changes in demand and supply and adjust their operations accordingly. Additionally, LPG companies can maintain strategic inventories to ensure a reliable supply of LPG during supply disruptions, and develop risk management strategies to assess and mitigate the financial risks associated with economic or financial crises.

To mitigate the risk of supply disruption due to natural or man-made disasters, LPG companies can develop and implement contingency plans and disaster recovery strategies. These may include diversifying supply sources and transportation routes, maintaining strategic inventories, investing in backup power systems and other forms of infrastructure resilience, and developing crisis communication plans. Additionally, companies can leverage technology to monitor and track supply chain performance and identify potential disruptions before they occur.

To mitigate the risk of regulatory compliance failures, LPG companies must maintain robust compliance programs that include regular risk assessments, training, monitoring, and reporting. Additionally, companies can implement compliance management software and other technology tools to track and manage regulatory requirements and develop relationships with regulators to stay abreast of changes in regulations and best practices. By maintaining robust compliance programs and investing in technology and relationships with regulators, LPG companies can mitigate these risks and ensure the sustainability and profitability of their operations.

This study on the LPG supply chain can have significant policy implications for improving the safety, sustainability, and resilience of the supply chain. The study can identify gaps in existing regulatory frameworks, infrastructure investments needed, the importance of emergency response plans, guidelines for risk management, and areas requiring capacity building. By implementing policies and strategies that address the risks identified in the study, governments, regulators, and industry stakeholders can help ensure the long-term viability of the LPG supply chain while contributing to the achievement of sustainable development goals.

5.5. Implications for Sustainability

The risk analysis of the LPG supply chain is closely related to sustainable development goals (SDGs) because it helps identify and mitigate risks that could negatively impact economic, social, and environmental sustainability. The SDGs are a set of 17 goals adopted by the United Nations in 2015 to address global challenges related to poverty, inequality, climate change, and other issues.

The LPG supply chain plays an essential role in achieving several of the SDGs, including Goal 7 (affordable and clean energy), Goal 9 (industry, innovation, and infrastructure), Goal 11 (sustainable cities and communities), and Goal 13 (climate action). However, achieving these goals requires managing risks that could undermine the sustainability of the LPG supply chain.

For example, the top-ranked risk factor in the LPG supply chain, price fluctuations due to changes in demand or supply, geopolitical events, or regulatory changes, can impact the affordability and accessibility of LPG, which are critical for achieving SDG 7. By analyzing this risk and implementing appropriate risk management strategies, such as diversifying supply sources or investing in storage infrastructure, LPG companies can help ensure the affordability and accessibility of LPG.

Similarly, the fourth-ranked risk factor in the LPG supply chain, supply disruption due to natural or man-made disasters, can impact the resilience and reliability of LPG supply chains, which are essential for achieving SDG 9. By analyzing this risk and implementing appropriate risk management strategies, such as developing contingency plans and investing in backup power systems, LPG companies can help ensure the resilience and reliability of LPG supply chains.

SDG 11 aims to make cities and human settlements safe, resilient, inclusive, and sustainable. The LPG supply chain plays a crucial role in achieving this goal by providing an affordable and accessible source of clean energy for cooking and heating, particularly in urban areas. However, risks such as supply disruption due to natural or man-made disasters or cybersecurity breaches could disrupt the reliability and resilience of the LPG supply chain, making it challenging to achieve SDG 11. By identifying and mitigating these risks, policymakers and industry stakeholders can ensure the sustainability and resilience of the LPG supply chain, thereby contributing to the achievement of SDG 11.

SDG 13 aims to take urgent action to combat climate change and its impacts. The use of LPG as a cleaner-burning fossil fuel compared to traditional fuels such as wood or coal can help reduce greenhouse gas emissions and contribute to achieving SDG 13. However, risks such as regulatory compliance failures or accidents during the transportation or handling of LPG could lead to environmental damage and undermine the sustainability of the LPG supply chain. By effectively managing these risks, policymakers and industry stakeholders can ensure the sustainability and environmental responsibility of the LPG supply chain, contributing to the achievement of SDG 13.

Therefore, the risk analysis of the LPG supply chain is closely related to sustainable development goals, as it helps identify and mitigate risks that could impact economic, social, and environmental sustainability. By effectively managing these risks, LPG companies can help ensure the sustainability and profitability of their operations while contributing to the achievement of the SDGs.

Chapter -6 Conclusions and Recommendations

6.1. Conclusions

This study aimed to enhance the resilience of the LPG supply chain through risk analysis during the global political crisis and post-COVID-19 era. The study identified the major risk factors and prioritized them using MCDM techniques, including AHP-TOPSIS and AHP-PROMETHEE. The results revealed that "Impact on business" and "Probability of occurrence" were the two most weighted criteria, while "Price fluctuations due to changes in demand or supply, geopolitical events, or regulatory changes", "Cybersecurity breaches", and "Economic or financial crises" were identified as the top three risks. The study provides valuable insights for managers and policymakers to improve the resilience of the LPG supply chain. The findings suggest that diversifying supply sources, investing in storage infrastructure, developing contingency plans, and investing in backup power systems could help mitigate the identified risks.

6.2. Recommendations

There are some limitations to this study. First, the risk factors and criteria used in this study may not be exhaustive, and other factors may need to be considered in different contexts. Second, this study relied on expert opinions, and there may be differences in opinions among experts.

Future studies can address these limitations by considering additional risk factors and criteria and incorporating more diverse stakeholder perspectives. Moreover, fuzzy or grey-based MCDM techniques can be incorporated with the methods to mitigate the vagueness of human decision-makers. A machine learning-based program can be developed following the framework in this study which can deal with real-time data and incorporate more experts from different geographic locations throughout the world. Additionally, future research can explore the potential impacts of the identified risk factors on achieving sustainable development goals. Overall, this research provides a foundation for further investigation into enhancing the resilience of the LPG supply chain in the context of global challenges.

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APPENDIX A

Table A1. Sample questionnaire for collecting experts' opinions to find criteria weights

Question	**Response**
How important do you think the Probability of occurrence (C1) is over the Impact on business (C2)?	
How important do you think the Probability of occurrence (C1) is over the Difficulty of mitigation (C3)?	
How important do you think the Probability of occurrence (C1) is over the Time sensitivity (C4)?	
How important do you think the Probability of occurrence (C1) is over the Supplier criticality (C5)?	
How important do you think the Probability of occurrence (C1) is over the Geographic location (C6)?	
… …	
How important do you think Supplier criticality (C5) is over the Geographic location (C6)?	

Table A2. Sample questionnaire for collecting experts' opinions to prioritize the risks

Code	**Criteria** / **Risk Factors**	**Response**					
		C1	**C2**	**C3**	**C4**	**C5**	**C6**
R1	Supply disruption due to natural or man-made disasters such as pandemics or war						
R2	Price fluctuations due to changes in demand or supply, geopolitical events, or regulatory changes						
…	… … … … … … … … … … … … … …						
R17	Supply disruptions due to labor strikes, protests, or other forms of civil unrest						

APPENDIX B

Table B1. A sample pair-wise matrix of an expert for the AHP method

	C1	C2	C3	C4	C5	C6
C1	1.00	0.50	5.00	3.00	2.00	5.00
C2	2.00	1.00	7.00	5.00	4.00	9.00
C3	0.20	0.14	1.00	0.33	0.33	1.00
C4	0.33	0.20	3.00	1.00	0.50	2.00
C5	0.50	0.25	3.00	2.00	1.00	2.00
C6	0.20	0.11	1.00	0.50	0.50	1.00

Table B2. A sample decision matrix of an expert for the risk prioritization

Criteria / Risks	C1	C2	C3	C4	C5	C6
R1	4.00	7.00	7.00	5.00	6.00	8.00
R2	6.00	8.00	5.00	8.00	6.00	5.00
R3	5.00	5.00	3.00	6.00	1.00	2.00
R4	5.00	8.00	8.00	9.00	5.00	2.00
R5	3.00	8.00	6.00	9.00	4.00	5.00
R6	2.00	4.00	2.00	7.00	5.00	1.00
R7	3.00	5.00	6.00	7.00	4.00	4.00
R8	3.00	4.00	3.00	3.00	3.00	3.00
R9	1.00	8.00	3.00	7.00	2.00	1.00
R10	1.00	4.00	1.00	1.00	2.00	3.00
R11	3.00	6.00	4.00	3.00	8.00	2.00
R12	2.00	5.00	6.00	5.00	2.00	1.00
R13	2.00	6.00	2.00	6.00	2.00	2.00
R14	1.00	4.00	8.00	8.00	6.00	3.00
R15	1.00	1.00	5.00	5.00	3.00	7.00
R16	4.00	7.00	7.00	8.00	7.00	6.00
R17	2.00	5.00	6.00	8.00	6.00	3.00