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ABSTRACT

Relief organisations face significant logistical challenges in the aftermath of natural disasters, characterised by volatile environments. Effective risk management in these contexts hinges on the identification, evaluation, and mitigation of potential risk events. This study addresses this critical need by aiming to identify and prioritise the most critical strategies to improve resilience. To achieve this, a novel framework, the Fuzzy Analytical Hierarchy Process - A fuzzy Technique for Order Performance by Similarity to Ideal Solution (FAHP-FTOPSIS), is proposed. An empirical application demonstrates that this framework effectively and systematically prioritises strategies for mitigating risks. This study examined existing mitigation strategies and identified eight that are particularly significant. Among these, collaboration and coordination, flexible transportation capabilities, and flexible supply bases emerged as the three most critical mitigation strategies for emergency supply chains. This finding emphasises the importance of prioritising these critical strategies in the development of strategic emergency supply chain plans. The practical implementation of these strategies, substantiated by empirical data from credible sources, would significantly enhance the preparedness of stakeholders and relief actors. This translates to a proactive ability to anticipate and respond to potential risk factors, ultimately leading to a more effective response to natural disasters.

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Analytic hierarchy process; emergency supply chain; empirical study; fuzzy logic; risk analysis; TOPSIS

1. Introduction

The COVID-19 pandemic struck the globe and caused unprecedented crises. This disaster is considered the most severe pandemic of this century (Kumar, Singh, and Shahgholian 2024). Similarly, the experience of the 7.7 magnitude earthquake that hit Turkey and Syria in February 2023 shows that disasters continue to cause loss of human life, environment damage, infrastructure disruption, and economic loss (IFRC 2023). The Emergency Event Database (EM-DAT) documented 432 natural disasters around the world in 2021. In total, these were responsible for 10,492 fatalities, affected an estimated 101.8 million people, and resulted in about 252.1 billion US$ in economic losses. Throughout all continents, Asia bore the brunt of the disasters, experiencing 40% of them and being responsible for 49% of the deaths and 66% of the affected population. Even though fatalities and impacted populations were lower in 2021 than they had been in previous years, more disasters occurred that year, causing extensive economic losses. The United States of America (USA) was hit by five of the top ten most economically costly disasters in 2021, totalling 112.5 billion US$

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in damages (CRED 2022). Natural disasters have been responsible for an average of 45,000 deaths yearly over the past decade, or 0.1% of all deaths globally (Ritchie, Rosado, and Roser 2022). Hurricane Dorian, the COVID-19 pandemic, Cyclone Idai, the Beirut explosion, wildfires in Australia and the United States, floods in India and Pakistan, earthquakes and tsunamis in Turkey and Indonesia (Kanwal 2023) are examples of recent worldwide disasters. These occurrences reiterate that disasters are unpredictable, and they can occur in any place, at any time, with severe consequences (Carroll and Neu 2009; Day et al. 2012; Kovács and Spens 2007; Tomasini and Van Wassenhove 2009). The magnitude of loss and disruption caused by any given disaster depends not only on the nature of the calamity itself but also on the pre-existing financial, health, and social conditions in the region (Agarwal, Kant, and Shankar 2021). As a result, disasters will continue to bring serious negative effects and raise awareness that calls for swift measures to alleviate human suffering and speed up reaction and recovery efforts. In the immediate aftermath of a disaster, the various effects on the population and its surroundings generate different needs and require different approaches to meet those needs. Thus, disaster relief operations (DROs) become crucial and urgent, as it is essential for the safety and survival of those affected by the impacts of the disaster (Adem et al. 2018). As the number of natural and man-made catastrophes is projected to increase by a factor of five over the next 50 years, disaster relief is and will remain a dynamic industry (Thomas and Kopczak 2005). Aiding those in need during times of crisis has become a multibillion-dollar industry spanning borders and cultures (Carroll and Neu 2009). The increasing number and effects of disasters (Seifert, Kunz, and Gold 2018) put a focus on the need for relief organisations to develop and deploy well-functioning emergency supply chains, which are charged with transforming resources into tangible products and services and delivering them appropriately and cost-effectively (Polater 2021). According to Najafi, Eshghi, and Dullaert (2013), emergency supply chain activities play a crucial role in disaster relief operations, encompassing both affected individuals and commodities. Furthermore, emergency supply chain activities may be the most expensive aspect of any relief operations (Van Wassenhove 2006). The overall aim of any disaster relief operation should be the establishment and management of an efficient and effective emergency supply chain (Pettit and Beresford 2005), which necessitates the adoption of strategic approaches rather than an 'whatever it takes' approach.

Risk management is vital in emergency supply chains due to the high uncertainty of their operating environment and the wide range of dangers to which they are vulnerable. An already dire situation might worsen if the ESC were to be disrupted (McLanchlin, Larson, and Khan 2009). The 2004 Indian Ocean tsunami aftermath illustrated the impact of disruptions in the emergency supply chain. The international delivery of critical supplies to affected regions was considered inefficient – allocated aid supplies were overwhelming in amount and partly unsuitable: aid workers struggled with warehousing and distribution. The inadequate management of the emergency supply chain created bottlenecks in the stream of critical supplies (Buddas 2014; Tomasini and Van Wassenhove 2009; Van Wassenhove 2006). Without well-executed ESC activities, it is impossible to mount a proper response to any disaster. Moreover, no matter how good the preparation of emergency supply chain activities is, the execution of these activities may still fail since there are many forms of risks inherent in emergency relief. Delivering the 'right supplies', at the 'right time', to the 'right place', in the 'right quantities' and to the 'right people' are the critical success factors in the emergency supply chain management system (Dohale et al. 2024; Petrudi, Tavana, and Abdi 2020). However, there are a lot of potential problems that can arise during an emergency response, so it is essential to be aware of the circumstances that could compromise the ESCs (Thévenaz and Resodihardjo 2010). L'Hermitte et al. (2015) suggest investigating the ESC to learn more about the dangers and unknowns involved. Moreover, there is a need to ascertain the nature and frequency of the risks encountered and to correctly identify, categorise, analyse, and manage the severity of their consequences on the operations of the emergency supply chain.

Adaptable solutions to risks and uncertainties in demand, supply, and procedures are essential for relief organisations to operate effectively in disaster environments (Balcik and Beamon 2008).

This necessitates forethought, the ready deployment of appropriate resources, and efficient on-the-ground adaptation to a wide range of local conditions to ensure optimal operations. L'Hermitte et al. (2015) argue that an emergency supply chain's efficiency and effectiveness are directly tied to its agility and responsiveness in the face of external disturbances. This can only be achieved effectively by flexible (Blecken et al. 2009; Oloruntoba and Gray 2009) and economical supply networks (Jahre et al. 2016; McLanchlin, Larson, and Khan 2009; Pettit and Beresford 2009). During times of crisis, emergency supply chains tend to be lengthy, inefficient, and immature, leaving them vulnerable to more hazards and more likely to collapse. McLanchlin, Larson, and Khan (2009) have suggested that supply chain risk management is critical in the disaster relief context since an emergency supply chain operates in highly volatile environments, and a disruption to the supply chain can lead to or contribute to a disaster. Limited studies have linked risk management with emergency supply chains (Jahre 2017). However, none of these studies have attempted to empirically identify and evaluate relevant risk mitigation strategies in relation to the most critical emergency supply chain risk factors. Such a study will enable practitioners and policymakers to improve the emergency supply chain's robustness rapidly. Therefore, considering the complexities, the unique features of the emergency supply chain, and the high impact of disasters in recent times, this study attempts to close this gap and builds on the works of Jahre (2017) and Chukwuka et al. (2023) and addresses the calls for more investigations to link the emergency supply chain and risk management to ensure effective disaster relief operations. To meet the goal of the study, two critical objectives will be completed:

1. What are the prevalent risk factors in emergency supply chains?
2. What are the risk mitigation strategies currently implemented in the emergency supply chains and their respective priorities?

Specifically, this study develops a fuzzy Analytical Hierarchy Process (F-AHP) and the Fuzzy Technique for Order of Performance by Similarity to Ideal Solution (F-TOPSIS) methodology to identify and evaluate the currently implemented risk mitigation strategies in emergency supply chains. Stakeholders face decision-making challenges when attempting to investigate the degree of importance of various alternatives in vague and uncertain environments. Therefore, challenges with a lot of grey areas and lack of precision call for the use of fuzzy set theory proposed by Zadeh (1965). This study makes a significant contribution to the literature of emergency supply chain risk management considering that It is believed to be the first study on managing risks in emergency supply chains that utilises this FAHP-FTOPSIS methodology to critically evaluate and prioritise the risk mitigation strategies in relation to the most important risk factors. Incorporating the Fuzzy AHP and Fuzzy TOPSIS as an integrated methodology is what makes the model that has been proposed unique. This has been done so that the specific preferences of the decision maker can be considered when making a strategic decision regarding risk management in emergency supply chains. The methodology considers the uncertainties that are brought about by data that is not known. As a result, putting fuzzy logic theory into practice can assist relief organisations in resolving the issue of effectively managing uncertainty in decision-making promptly. Moreover, prioritising the risk mitigation strategies will help emergency relief professionals and policymakers better understand which approach is most important for the mitigation of respective risk factors, enhance the efficiency of the emergency supply chain, and achieve the overall goal of the disaster relief operation.

The rest of this study is structured as follows. Section 2 provides a rigorous literature review that covers the risk factors and mitigation strategies currently implemented in emergency supply chains. The Fuzzy AHP and Fuzzy TOPSIS methodology is detailed in section 3. Section 4 presents and describes the proposed Fuzzy AHP-Fuzzy TOPSIS methodology for the prioritisation of the risk mitigation strategies for emergency supply chains. A real-world example is conducted and explained in section 5. Finally, section 6 concludes the study.

2. Literature review

2.1. Risks in emergency supply chains

A typical emergency supply chain's main duty is to respond to disasters quickly and effectively by providing vital resources to especially vulnerable areas. Distributing assistance to those in need is one way that relief organisations can accomplish this goal. (Besiou, Stapleton, and Van Wassenhove 2011; Blecken 2010). Risks lead to supply chain issues, such as unanticipated changes in the flow of materials because of delays or disruptions (Chopra and Sodhi 2004). Since 'doing business requires the acceptance of some level of risk within organizations,' the presence of risk in supply chains is not a recent phenomenon (Olson and Wu 2010). According to Tummala and Schoenherr (2011), no supply chain can be risk-free because risk is the result of unforeseen events that prevent the supply chain from reaching its performance goals (Heckmann, Comes, and Nickel 2015). Additionally, it is impossible to stop an unfavourable or advantageous occurrence from happening. Organisations are now evaluating 'how vulnerable global supply chains' can be due to disruptions like crises and catastrophes (Wieland and Wallenburg 2012). Supply chain risk was described by Juttner, Peck, and Christopher (2010) as 'the possibility and impact of supply and demand mismatch.' As an expected outcome from an uncertain event,' Manuj and Mentzer (2008) defined supply chain risk. As another definition puts it, 'the likelihood and impact of unexpected macro and micro level events or conditions that adversely influence any part of a supply chain leading to operational, tactical, or strategic level failures or irregularities' (Ho et al. 2015). Disaster relief organisations face a variety of risks when transporting, storing, and distributing relief goods because logistics and supply chain activities take place in unpredictable and dynamic environments. These include supply uncertainties, unstable political environments, policy challenges, limited or incomplete information, and the possibility of socioeconomic and financial problems (Day 2014; L'Hermitte et al. 2016; Overstreet et al. 2011). Unpredictable demand is also discussed, including the quantity, timing, and location of necessary essential supplies. According to Baharmand, Comes, and Lauras (2017), risks arise as a result of a number of issues, such as incorrect assessment and misjudgements based on uncertainties (supply, demand, fleets, locations, etc.), challenging field conditions, the impact of the disaster on local infrastructure and labour, and structural differences between responders, particularly emergency relief organisations. Thomas and Kopczak (2005) cited a lack of expert logisticians, limited collaboration and coordination, manual supply chain processes, and insufficient assessments and planning as some of the difficulties that relief organisations face when delivering aid. The emergency supply chain faces difficulties due to a variety of factors, as discussed by Balcik et al. (2010). These include the sheer number of involved parties, the variety of donor expectations and financing structures, the lack of certainty surrounding disaster occurrence, resource scarcity, and an abundance of critical aid.

The management of risks in emergency supply chains is crucial due to the potential hindrance of the emergency supply chain's effectiveness, which could result in loss of lives. The responsibility lies with decision-makers and stakeholders to implement novel methodologies in their operational strategies (Stefanovic, Stefanovic, and Radenkovic 2009). To implement strategies aimed at mitigating risks within emergency supply chains, stakeholders and decision-makers must first acquire a comprehensive understanding of the different types of risks and the underlying factors that contribute to their emergence. This necessitates that emergency managers possess relevant knowledge and insights pertaining to the subject matter. The emergency supply chain during disaster response operations is susceptible to various potential issues, and extant literature on this topic is fragmented across a limited number of studies. The extant literature on supply chain management offers valuable insights and a clear understanding of the challenging and constraining factors that can have adverse effects on logistics and supply chain operations. The enhancement of operational performance in emergency management necessitates the deconstruction of the management process into pertinent components and facets in order to facilitate the overall management endeavour.

Hence, managers and decision-makers must focus their attention on the critical facets of emergency management. Various classifications of supply chain risks have been presented in the commercial sector through several studies. For example, Manuj, Gaudenzi, and Dittmann (2007) categorised risk into four groups: supply, process, demand, and security risks. Internal to the organisation, external to the organisation but internal to the supply network, and external to the supply network were the three categories used by Christopher and Peck (2004). In a similar vein, Pfohl, Gallus, and Thomas (2011) addressed the fact that risks associated with the supply chain could be categorised as risks that are internal to the focal business, risks that are related to suppliers, and risks that are external to the supply chain. Balcik and Beamon (2008) expounded on the risks associated with demand, supply, and process in the context of an emergency supply chain.

Economic, social, environmental, infrastructural, and political risks were the categories used by Chari et al. (2021) to group supply networks risks. According to Jahre (2017) there are two main categories of risk: abnormal and normal. They go on to explain how abnormal risks, like natural and man-made catastrophes, can affect normal risks, like those associated with supply, demand, and infrastructure. Relief organisations face intricate contextual factors, in addition to the risks and uncertainties related to demand and supply, during the provision of aid (L'Hermitte, Tatham, and Bowles 2014). In their study, Chukwuka et al. (2023) classified risk factors in emergency supply chains into two overarching categories, namely internal and external risks. These categories were further subdivided into four sub-categories, namely demand, supply, infrastructural, and environmental risks. Additionally, the authors identified 11 distinct types of risks, including forecast, inventory, procurement, supplier, quality, transportation, warehousing, systems, disruption, social, and political risks. Building upon the groundwork established by Chukwuka et al. (2023), this study utilises their classification and risk factor descriptions (as detailed in Table 1) as a springboard for further investigation. Chukwuka et al. (2023) commendably compiled a comprehensive risk database specifically designed to aid stakeholders engaged in disaster relief operations. The very nature of disasters necessitates the deployment of specialised emergency supply chains (ESCs). These ESCs, however, are susceptible to disruption by a multitude of risk factors, the precise nature of which can vary depending on the specific disaster. Nonetheless, a comprehensive understanding of the global emergency supply chain risk landscape remains paramount in effectively mitigating the overall impact of disasters.

2.2. Managing risks in emergency supply chains

Effective supply chain risk management aims to prevent unanticipated events by methodically putting into place suitable risk mitigation strategies (Juttner et al. 2003; Norrman and Jansson 2004; Juttner 2005). Given the potentially disastrous effects of risk occurrences, supply chain risk management literature continues to expand and attract significant interest from top managers. While preparedness and strategic planning are becoming more standard in emergency relief, the unpredictable nature of large-scale disasters in terms of magnitude, timing, location, and severity makes them very challenging to plan for in any detail (Kovacs and Spens 2007). To better understand how relief organisations prepare for emergency logistics, Jahre (2017) performed research to establish a connection between emergency logistics and supply chain risk management. The author discovered that relief actors employ several of the proposed strategies, especially those involving strategic stocks, postponement, and collaboration. Choi et al. (2010) included risk management in their emergency relief distribution research in East Africa because some actors demand risk premiums. Emergency supply chains are uncommon since relief goods are free to recipients. Thus, certain relief actors, such as transport providers in disaster zones, purposefully take risks in their economic methods. This shows that service providers may profit from emergency supply chains by adjusting service provision and charging a 'risk premium'. Tay et al. (2022) identified the dominant supply chain risk factors in each phase of the disaster management cycle and investigated how supply chain strategies can be used to mitigate the risk factors respectively. Chari et al. (2021)

Table 1. Summary of risk factors in emergency supply chains.

Main category	Sub-category	Risk type	Specific risk factors	References
Internal	Demand	Forecast	Poor demand projection (R1)	Jahre and Heigh (2008), Buddas (2014), Holguin-Veras et al. (2014)
			Distortion of information (R2)	Stauffer, Pedraza-Martinez, and Van Wassenhove (2016), Jahre et al. (2016)
		Inventory	Limited life cycle of relief supplies (R3)	Kovacs and Falagara Sigala (2021)
	Supply	Supplier	Inadequate supplier capacity (R4)	Kim, Ramkumar, and Subramanian (2019), Baharmand, Comes, and Lauras (2017), Tayal and Singh (2019), Chirra and Kumar (2018)
			Poor level of supplier responsiveness (R5)	Jahre and Heigh (2008), McLanchlin, Larson, and Khan (2009), Choi et al. (2010), Kunz et al. (2015)
			Variation in transit time (R6)	Baharmand, Comes, and Lauras (2017), Oloruntoba and Gray (2006), Kim, Ramkumar, and Subramanian (2019)
		Procurement	Non-compliance of supply contracts (R7)	Aghajani and Torabi (2020), John and Ramesh (2016), Baldini et al. (2012), Balcik et al. (2010)
			Purchasing key supplies from a single source (R8)	Kovacs and Falagara Sigala, (2021), Kovacs and Spens (2009), Baldini et al. (2012)
			Long-term vs short-term contracts (R9)	L'Hermitte and Nair (2021), Dubey, Altay, and Blome (2019), Kim, Ramkumar, and Subramanian (2019), Olanrewaju, Dong, and Hu (2020)
		Quality	Defective or damaged relief supplies (R10)	Holguin-Veras et al. (2014), Kovacs and Spens (2009), Holguin-Veras et al. (2012)
			Wrong or unsolicited relief supplies (R11)	Kovacs and Spens (2007), Kovacs and Spens (2009)
			Counterfeit relief supplies (R12)	Holguin-Veras et al. (2012), Kovacs and Spens (2009)
	Infrastructural	Transportation	Damaged transport infrastructure (R13)	Kovacs and Spens (2009), Kovacs and Spens (2007), John and Ramesh (2016), Barbarosoğlu, Özdamar, and Cevik (2002), Chandes and Paché (2010)
			Absence of alternative transport modes (R14)	Kovacs and Falagara Sigala, (2021), Ben-Tal et al. (2011)
			Ineffective last-mile delivery (R15)	Oloruntoba and Kovács (2015), Van Wassenhove (2006), John and Ramesh (2016), Ben-Tal et al. (2011)
			Theft of relief supplies and resources (R16)	Baldini et al. (2012), Pettit and Beresford (2005), Cassidy (2003)
		Warehousing	Damaged warehousing facilities (R17)	Kovacs and Spens (2009), Kunz and Reiner (2012), John and Ramesh (2016), Baldini et al. (2012), Altay, Prasad, and Sounderpandian (2009), Chandes and Paché (2010), Chari et al. (2021)
			Limited holding capacity of facilities (R18)	Kim, Ramkumar, and Subramanian (2019), Baharmand, Comes, and Lauras (2017), Tayal and Singh (2019), Maghsoudi and Moshtari (2021)
		Systems	Poor I.T infrastructure (R19)	Schulz and Blecken (2010), Kabra and Ramesh (2015), Chari et al., (2021)
			Absence of transparency in information dissemination (R20)	Altay and Pal (2014), Kovacs and Spens (2007)
			Presence of delays during information transmission (R21)	Kumar and Harvey (2013), Kovacs and Spens (2007), Altay and Pal (2014), and Altay (2008).
External	Environmental	Disruption	Impact of follow-up disasters (R22)	Petrudi, Tavana, and Abdi (2020), Cozzolino, Rossi, and Conforti (2012), Holguin-Veras

(*Continued*)

Table 1. Continued.

Main category	Sub-category	Risk type	Specific risk factors	References
				et al., (2014), L'Hermitte et al. (2016), Stauffer et al. (2016)
			War and terrorism (R23)	Listou (2008), McLanchlin, Larson, and Khan (2009), Choi et al. (2010), Jahre and Jensen (2010), Buddas (2014)
		Social	Poor communication (R24)	Altay, Prasad, and Sounderpandian (2009), L'Hermitte and Nair (2021), Altay et al. (2018), Kim, Ramkumar, and Subramanian (2019), John and Ramesh (2016), Balcik et al. (2010)
			Corrupt practices (R25)	Altay (2008), Maxwell et al. (2012), Schultz and Søreide (2008)
			Sexual and gender abuses (R26)	Kunz and Reiner (2012), Kovacs and Spens (2009), Oloruntoba (2005), Maon, Lindgreen, and Vanhamme (2009)
		Political	Absence of legislative and supportive rules that influence relief operations (R27)	Kunz and Reiner (2016), Day et al. (2012), L'Hermitte, Tatham, and Bowles (2014), Behl and Dutta (2019), Maon, Lindgreen, and Vanhamme (2009), Oloruntoba (2005), Maghsoudi and Moshtari (2021)
			Sanctions and constraints that hinder stakeholder collaboration (R28)	Sandwell (2011), Behl and Dutta (2019), Maon, Lindgreen, and Vanhamme (2009), Oloruntoba (2005), Altay, Prasad, and Sounderpandian (2009).

Source: Chukwuka et al. (2023)

investigated whether barriers prevented emergency supplies from reaching those in Zimbabwe whom Cyclone Idai hit. They found that social, political, economic, and infrastructural uncertainties impeded emergency relief efforts after Cyclone Idai. The study also discovered that efforts to lessen environmental and infrastructure problems did not consider different modes of transportation and communication, such as drone technology. There was either insufficient emergency aid or the aid that did arrive either arrived too late or was damaged. Unfortunately, there were no well-thought-out strategies in place to safeguard the emergency supply chain against the possibility of shortage, theft, or spoilage. Wild and Zhou (2011) were interested in the relationship between ethical procurement and risk. Schniederjans, Ozpolat, and Chen (2016) explored the risks associated with information sharing via cloud computing to enhance cooperation. L'Hermitte et al. (2016) used 'risk' to discuss adaptation and long-term operations. Even if such operations are stable and regular, such risks exist, and adaptation is needed.

In general, the commercial supply chain and the emergency supply chain both have some parallels and differences, which have been observed and examined by several writers (e.g. Balcik et al. 2010; Ertem, Buyurgan, and Rossetti 2010; Van Wassenhove 2006). The primary objective of a typical SC, which is 'getting the right commodities, at the right time, to the right place, and distributing them to the right people,' is unquestionably transferable to the overarching structure for disaster relief (Van Wassenhove 2006). In addition, the fundamental concept of risk management regarding commercial supply chains, which aims to manage risks (including disasters), uncertainties, and vulnerabilities in a timely manner while also being cost-efficient (Kovács and Tatham 2009), is generally in line with the corresponding emergency supply chain risk management framework. Extant literature has suggested various mitigation strategies to overcome supply chain risks, including agility, flexibility, responsiveness, and resilience (Gupta, Ivanov, and Choi 2021; Heckmann, Comes, and Nickel 2015; Jüttner and Maklan 2011; Kim, Chen, and Linderman 2015; Sigala et al. 2022; Ye et al. 2022). The goal is to construct supply chains that are adaptable, dynamic, and nimble so that organisations can either build in extra capacity for unexpected demand spikes or gain access to it in other ways. (Finkenstadt and Handfield 2021; Sigala et al. 2022; Sodhi and

Tang 2021). However, gaining access to surge power typically necessitates either doing business with additional suppliers or forming public-private partnerships. (Balcik et al. 2010; Tomasini and Van Wassenhove 2009). The availability of shared surge capabilities depends on the supply chain's visibility, i.e. the ability to see what is coming and what is going out in the supply chain (Handfield et al. 2020). Duran et al. (2013) acknowledge that the development of emergency response capacity, as well as preparedness, are essential components of effective aid, and they suggest that the assurance of high availability of relief supplies through advanced procurement is the best way to accomplish this goal (inventory pre-positioning). There is widespread agreement amongst researchers and practitioners of emergency response that pre-positioning relevant supplies at strategic places is an effective way to smooth over initial surges in demand (Altay, Prasad, and Sounderpandian 2009; Comes, Van de Walle, and Van Wassenhove 2020). Roh, Shin, and Seo (2018) structured a two-step methodology using fuzzy AHP and fuzzy TOPSIS to evaluate prepositioned warehouse locations for relief organisations. They suggested that national stability is considered the most critical factor for strategic prepositioning. The rationale behind national strategic reserves is comparable to that of emergency relief prepositioning (Handfield et al. 2020; Kachali et al. 2018; Sigala et al. 2022).

A distinct approach to mitigating risk involves ensuring the interoperability of items, identifying interdependencies, and preparing joint modules or even kits. (Vaillancourt 2016). In the humanitarian context, kitting is used to guarantee that all necessary supplies are on hand at the right time and that the response is coordinated between different organisations (Jahre and Fabbe-Costes 2015; Kovács and Falagara Sigala 2021; Vaillancourt 2016). As a means of mitigating disruptions, it is also advised to employ numerous sourcing methods to address shortages from various suppliers and geographical areas. (Berger and Zeng 2006; Yang, Wang, and Zhao 2018). Dual sourcing was recommended by Iakovou et al. (2014) as a proactive risk mitigation sourcing technique in disaster relief operations. Mitigation strategies used to ensure the availability of items when they are required include pre-qualifications of suppliers and framework agreements for quicker scaling up to meet surge demand. (Gossler et al. 2019). Naturally, the reduction of lead times is the primary concern of a normal emergency supply chain, and operational costs are not given as much consideration during the very first few hours after a disruption has taken place. The emergency supply operates in volatile contexts, necessitating the development of strategies and practices that provide them with the ability to react to risks and uncertainties in demand, supply, and operations (Balcik and Beamon 2008). Table 2 presents a summary of supply strategies currently implemented in disaster relief operations. One would suggest borrowing concepts from the commercial sector, but there are several structural, operational, and procedural differences between commercial and emergency supply chains. These variables include things like lead times, political climate, social media, performance monitoring, and equipment. Furthermore, relief organisations require specialised and ad hoc supply chain disruption management solutions in emergency relief operations. Existing research suggests that the operational effectiveness of emergency supply chains is contingent on their capacity to adapt rapidly to external interruptions and to conduct dynamic operations (L'Hermitte et al. 2015). To do this, supply chains must be responsive (Blecken et al. 2009; Merminod, Nollet, and Pache 2014; Oloruntoba and Gray 2009) and cost-effective (McLanchlin, Larson, and Khan 2009; Pettit and Beresford 2009). Effective emergency relief requires two things: first, that supplies get to the disaster location quickly, and second, that enough goods get there to make a difference.

3. Methodology

This study used fuzzy logic, AHP, and TOPSIS to explore, suggest, and prioritise risk mitigation strategies in emergency supply chains. The method has three steps (Patil and Kant 2014). A comprehensive literature review, high-level surveys and interviews were utilised to retrieve risk factors and potential mitigation strategies. In the second and third phases, fuzzy AHP estimated

Table 2. Supply chain strategies for managing emergency supply chains.

Supply Chain strategies	Emergency Supply chain strategies and Related works
Centralisation	Centralised prepositioning (Listou 2008), Centralised decision-making (Thévenaz and Resodihardjo 2010), and centralised fleet hubs (Pedraza Martinez, Stapleton, and Van Wassenhove 2011).
Collaboration	Coordination (Akhtar, Marr, and Garnevska 2012; Balcik et al. 2010; Dubey et al. 2018; Kabra and Ramesh 2015; Moshtari and Gonçalves 2017; Singh, Gupta, and Gunasekaran 2018; Van Wassenhove 2006; Vega 2018), supplier relations (Kovacs and Spens 2009), commercial-humanitarian cooperation (Majewski, Navangul, and Heigh 2010), collaborative procurement (Sigala et al. 2022; Wild and Zhou 2011), civil-military coordination (Heaslip, Sharif, and Althonayan 2012), adaptability (Dubey and Gunasekaran 2016), and orchestrating networks (Oloruntoba and Kovács 2015), Swift trust and commitment (Dubey et al. 2020; Dubey, Altay, and Blome 2019; Kabra and Ramesh 2015; Prasanna and Haavisto 2018)
Flexible supply base	Multiple suppliers (Cozzolino, Rossi, and Conforti 2012; Ertem, Buyurgan, and Rossetti 2010; Kovacs and Sigala 2021; Haque and Islam 2018; Kumar, Singh, and Shahgholian 2024; Yang, Wang, and Zhao 2018), asset transfer mechanism (Bhattacharya, Hasija, and Van Wassenhove 2014), Dual sourcing (Iakovou et al. 2014), flexible sourcing (Day 2014), buttressing supply chains (Sodhi and Tang 2014), adaptive entity capacity (Day 2014), and arms-length and transactional (Oloruntoba and Kovács 2015)
Flexible supply contracts	Flexible order quantities (Lodree 2011; Torabi et al. 2018), framework agreements (Balcik and Ak 2014; Gossler et al. 2019; Sigala et al. 2022), and options contract (Aghajani, Torabi, and Heydari 2020; Liu et al. 2019; Rabbani, Arani, and Rafiei 2015; Wang et al. 2015)
Flexible transportation	Operational mix for fleet (Besiou, Pedraza-Martinez, and van Wassenhove 2014), alternative transport modes (Ertem, İşbilir, and Şahin Arslan 2017; Holguín-Veras et al. 2012; Kovacs and Sigala 2021; Maghfiroh and Hanaoka 2020; Yadav and Barve 2015)
Information sharing	Demand signal visibility (Day et al. 2012; Ergun et al. 2014), visibility (Finkenstadt and Handfield 2021; Handfield et al. 2020; Maghsoudi and Pazirandeh 2016; Sigala et al. 2022; Kumar and Singh 2022), alignment (Dubey et al. 2021; Dubey and Gunasekaran 2016; L'Hermitte et al. 2016), and cloud computing (Schniederjans, Ozpolat, and Chen 2016)
Make-and-buy	Logistics outsourcing (Bealt, Fernández Barrera, and Mansouri 2016; Kim, Ramkumar, and Subramanian 2019; Majewski, Navangul, and Heigh 2010; Nurmala, de Leeuw, and Dullaert 2017; Schulz 2009; Sigala and Wakolbinger 2019), and resource sharing (Maghsoudi and Pazirandeh 2016)
Postponement	Non-earmarking of items (Jahre and Heigh 2008), rosters (Kovács and Tatham 2009), non-earmarked funding (Besiou, Pedraza-Martinez, and van Wassenhove 2014), and standardisation (Jahre and Fabbe-Costes 2015)
Speculation	Full speculation (Listou 2008), decentralised prepositioning (Jahre and Heigh 2008), and unsolicited goods (Holguín-Veras et al. 2014)
Strategic stock	Secure location (Hale and Moberg 2005; Sharifi-Sedeh et al. 2020; Torabi et al. 2018), pooling resources (Kovács and Tatham 2009), vendor-managed inventory (Van Wassenhove and Pedraza Martinez 2012), prepositioning (Kachali et al. 2018; Kumar, Singh, and Shahgholian 2024; Kunz et al. 2015; Sigala et al. 2022; Toyasaki et al. 2017), temporary fleet hubs (Stauffer et al. 2015), and distribution warehouses (Hong, Jeong, and Feng 2015)
Decision policy/procedures	Day et al. (2012); Kunz and Gold (2015); Holguín-Veras et al. (2012); Kabra and Ramesh (2015); Yadav and Barve (2015); Singh, Gupta, and Gunasekaran (2018)
Cash-based interventions	Fenton et al. (2014), Heaslip, Haavisto, and Kovács (2016; 2018)
Risk awareness/Knowledge management	Tatham and Spens (2011); Yadav and Barve (2015); Pettit and Beresford (2009); Singh, Gupta, and Gunasekaran (2018)

Source: Adapted from Jahre (2017)

risk factor weights and fuzzy TOPSIS ranked the risk mitigation strategies for emergency supply chains.

3.1. Fuzzy AHP

The Analytical Hierarchy Process (AHP) is a general theory of measurement developed by Satty in 1980. It is used to derive ratio scales from both discreet and continuous paired comparisons. These comparisons may be taken from actual measurements or from a fundamental scale that reflects the relative strength of preferences and feelings. According to Vaidya and Kumar (2006), the AHP has been a tool for decision-makers and researchers since its inception. In addition, the AHP tool is suggested to be one of the most widely used multi-criteria decision-making tools. The AHP solves multi-criteria (or attribute) decision-making (MCDM) problems, particularly when involving qualitative assessment parameters. An MCDM problem could be solved analytically if all the parameters are well-defined and quantifiable. Unfortunately, many evaluation criteria are subjective and qualitative. Although AHP is a celebrated method for MCDM problems, particularly when qualitative assessment is needed, it cannot process uncertain variables (Wang et al. 2008). The pairwise comparison, the essence of AHP, introduces imprecision because it requires the judgments of experts. In practical cases, experts might not be able to assign exact numerical values to their preferences due to limited information or capability (Liu, Eckert, and Earl 2020; Xu and Liao 2013). Confronting these uncertainties requires the application of some distinct methods, such as fuzzy set theory.

Fuzzy set theory is a mathematical approach developed by Zadeh (1965) to deal with uncertain, imprecise, vague, and ambiguous information retrieved from computational perception. Fuzzy set theory adopts fuzzy logic to mathematically point out uncertainty and vagueness linked with notional activities of human beings such as thinking and reasoning. Fuzzy logic encompasses flexible and robust attributes that can enable tools to overcome real-world problems with uncertain intrinsic parameters, which are approximate values rather than exact. Therefore, combining fuzzy set theory and AHP will extend Saaty's AHP and reduce vagueness and uncertainty in decision-making. An explanation of the fuzzy AHP method is presented as follows.

1. Structure problem hierarchy.

   This is the first step of the analysis. Here, a hierarchy is developed to illustrate the problem. The hierarchy consists of a goal, a set of criteria, sub-criteria, and sub-sub criteria.
2. Construct a fuzzy pairwise comparison matrix.

   Traditionally, AHP utilises the nine-point Likert scale for pairwise comparison of attributes, which introduces uncertainty and bias to expert judgment. The Fuzzy-AHP utilises linguistic preference to eliminate uncertainty and bias. Table 3 presents the linguistic terms adopted in this research to inform the degree of relevance of an attribute over another (pair-wise comparison). Here, linguistic terms are transformed into definite values (TFNs).
3. Aggregation for group decisions and weight calculation

Each pairwise comparison matrix represents the judgments of one expert. There is a need to aggregate the judgments to achieve a collective consensus of all experts. The traditional AHP encompasses two basic approaches for aggregating individual preferences into a group preference, including aggregation of individual judgments (AIJ) and aggregation of individual priorities (AIP). This is also applicable in the fuzzy AHP. Aggregation of individual judgment allows the development of the group judgment matrix from the individual judgment matrices. AIJ is most often performed using geometric mean operations. Geometric mean operations are commonly used within the application of the AHP for aggregating group decisions, and only the geometric mean satisfies the unanimity and homogeneity condition. Following the aggregation of expert judgments for a consensus decision, the weight of each attribute and sub-attribute is calculated. In this research,

Table 3. Triangular fuzzy conversation scale for fuzzy-AHP.

Linguistic scale	Triangular fuzzy conversation scale	Triangular fuzzy reciprocal scale
Equal Importance	(1, 1, 1)	(1, 1, 1)
Weak Importance	(1, 3/2, 2)	(1/2, 2/3, 1)
Strong Importance	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Very Strong Importance	(2, 5/2, 3)	(1/3, 2/5, 1/2)
Absolute Strong Importance	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)

Source: (Chang 1996; Lee 2010)

the extent analysis method proposed by Chang (1996) and widely accepted by several researchers due to its simplicity is adopted. The ideology behind the method is concerned with estimating the extent of an attribute's satisfaction towards the research goal.

3.2. Fuzzy TOPSIS

Hwang and Yoon are credited with developing TOPSIS, a classic multi-criteria decision-making process (1981). The theory behind it is that the best option is the one that is furthest from the negative ideal solution (NIS) and closest to the positive ideal solution (PIS) (Patil and Kant 2014; Venkatesh et al. 2019). The PIS strives to achieve the reverse of what the NIS does, which is to maximise the benefit criteria while minimising the cost criteria (Venkatesh et al. 2019). Crisp values indicate subjective opinions in the classic TOPSIS technique. However, it is only sometimes possible to make precise measurements in practice.

Moreover, the prevalence of researcher bias has drawn criticism for TOPSIS's applicability (Afshar et al. 2011; Aydogan 2011). Therefore, fuzzy theory can be incorporated into TOPSIS, which not only aids in evaluating human inputs about values but also facilitates the investigation of criteria problems in ambiguous circumstances (Choudhary and Shankar 2012; Kuo, Tzeng, and Huang 2007; Sindhu, Nehra, and Luthra 2017; Sun 2010). Relying on linguistic value rather than crisp value is the way to go. Several studies have incorporated fuzzy TOPSIS. For example, Venkatesh et al. (2019) proposed a fuzzy AHP-TOPSIS model for supply partner selection in continuous aid humanitarian supply chains. Kabra and Ramesh (2015) developed a fuzzy AHP-TOPSIS model to explore the barriers to coordination in humanitarian supply chains. Nazam et al. (2015) formulated the fuzzy AHP-TOPSIS framework to calculate the weight of each risk criterion and rank the risks associated with implementing green supply chain management practices in a fuzzy environment. This was done to rank the risks associated with green supply chain management practices. When it comes to an understanding of how important it is to carry out the appropriate risk assessment when putting green supply chain initiatives into action, researchers and practitioners can benefit from the models that have been proposed.

The procedures for building the Fuzzy-TOPSIS analysis are described below (Patil and Kant, 2014),

STEP 1: *Choose the linguistic rating values for the alternative with respect to the criteria.*

Let us assume there are m possible alternatives called $A = \{A_1,\ A_2,\ \ldots,\ A_m\}$ which are to be evaluated against the criteria, $C = \{C_1,\ C_2,\ \ldots,\ C_n\}$. The criteria weights are denoted by w_j $j = \{1,\ 2,\ \ldots,\ n\}$. The performance rating of each expert $D_k(k = 1, 2,\ \ldots,\ K)$ for each alternative $A_i\ (i = 1, 2,\ \ldots,\ m)$ with respect to the criteria $C_j(j = 1, 2,\ \ldots,\ n)$ are denoted by $\tilde{R}_k = \tilde{X}_{ijk}(i = 1, 2,\ \ldots,\ m; j = 1, 2,\ \ldots,\ n; k = 1, 2,\ \ldots,\ K)$ membership function $\mu\tilde{R}k(x)$. This study will use the scale presented in Table 4.

STEP 2: *Calculate the aggregate fuzzy rating for all alternatives.*

If the fuzzy ratings for all experts are described as TFN, $\tilde{R}_k = (ak,\ bk, ck),\ k = 1, 2,\ \ldots, K$ were,

$$a = \min_k \{ak\}, \quad b = \frac{1}{K}\sum_{k-1}^{k} b_k, \quad c = \max_k \{c_k\} \tag{1}$$

Table 4. Linguistic scale for fuzzy-TOPSIS.

Linguistic Judgements	Explanations	Membership function
Equal Importance	Two activities contribute equally to the objective	(1,1,3)
Weak Importance	Experience and Judgement slightly favour one over another	(1,3,5)
Strong Importance	Experience and Judgement strongly favour one over another	(3,5,7)
Very strong Importance	One attribute is favoured very strongly over another	(5,7,9)
Absolute strong Importance	One attribute over the other is of the highest possible order of affirmation.	(7,9,11)

Source: (Patil and Kant, 2014)

If the fuzzy rating of the kth decision maker is $\tilde{X}_{ijk} = (a_{ijk}, b_{ijk}, c_{ijk}),\ i = 1, 2, \ldots, m,\ j = 1, 2, \ldots n$ then the aggregated fuzzy ratings $\tilde{X}_{ij}$ of alternatives with respect to each criterion are given by $\tilde{X}_{ij} = (a_{ij}, b_{ij}, c_{ij})$, where

$$a_{ij} = \min_k \{a_{ijk}\},\ b = \frac{1}{K}\sum_{k-1}^{k} b_{ijk}, \quad c = \max_k \{c_{ijk}\} \tag{2}$$

STEP 3: *Construct the fuzzy decision matrix.*

The fuzzy decision matrix for the alternatives $(\widetilde{D})$ is constructed as follows:

$$C_1 C_2 C_n$$

$$(\widetilde{D}) = \begin{matrix} A_1 \\ A_2 \\ \cdots \\ \cdots \\ A_3 \end{matrix} \begin{bmatrix} \tilde{X}_{11} & \tilde{X}_{12} & \cdots & \cdots & \tilde{X}_{1n} \\ \tilde{X}_{21} & \tilde{X}_{22} & \cdots & \cdots & \tilde{X}_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ \tilde{X}_{m1} & \tilde{X}_{m2} & \cdots & \cdots & \tilde{X}_{mn} \end{bmatrix} i = 1,\ 2,\ \ldots, m{:}j = 1, 2, \ldots, n \tag{3}$$

STEP 4: *Construct the normalised fuzzy decision matrix.*

The raw data are normalised using linear scale transformation to bring the various criteria scales into a comparable scale. The normalised fuzzy decision matrix $\tilde{R}$ is given by:

$$\tilde{R} = [r_{ij}]_{m\times n},\ i = 1, 2, \ldots .m; j = 1, 2, \ldots, n, \tag{4}$$

Where,

$$\tilde{r}_{ij} = \left(\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*}, \frac{c_{ij}}{c_j^*}\right) \textit{ and } c_j^* = \max_i \{c_{ij}\}\ (\textit{benefit criteria}) \tag{5}$$

$$\tilde{r}_{ij} = \left(\frac{a_j^-}{c_{ij}}, \frac{a_j^-}{b_{ij}}, \frac{a_j^-}{a_{ij}}\right) \textit{ and } a_j^- = \min_i \{a_{ij}\}\ (\textit{cost criteria}) \tag{6}$$

STEP 5: *Construct the weighted normalised matrix.*

The weighted normalised matrix $\tilde{v}$ for criteria is computed by multiplying the weights (w_j) of evaluation criteria with the normalised fuzzy decision matrix $\tilde{r}_{ij}$.

$$\tilde{V} = [\tilde{v}_{ij}]_{m\times n}, \quad i = 1, 2, \ldots m; j = 1, 2, \ldots, n \textit{ where } \tilde{v}_{ij} = \tilde{r}_{ij}(.)W_j \tag{7}$$

Note that $[\tilde{v}_{ij}]_{m\times n}$ is a TFN represented by $(a_{ijk}, b_{ijk}, c_{ijk})$.

STEP 6: *Determine the fuzzy positive ideal solution (FPIS) and fuzzy negative ideal solution (FNIS).*

The FPIS and FNIS of the alternatives is computed as follows:

$$A^* = (\tilde{v}_1^*, \tilde{v}_2^*, \ldots, \tilde{v}_n^*) \textit{ where } \tilde{v}_j^* = (\tilde{c}_j^*, \tilde{c}_j^*, \tilde{c}_j^*) \textit{ and } \tilde{c}_j^* = \max_i \{\tilde{c}_{ij}\} \tag{8}$$

$$A^- = (\tilde{v}_1^-, \tilde{v}_2^-, \ldots, \tilde{v}_n^-) \textit{ where } \tilde{v}_j^- = (\tilde{a}_j^-, \tilde{a}_j^-, \tilde{a}_j^-) \textit{ and } \tilde{a}_j^- = \min_i \{\tilde{a}_{ij}\} \tag{9}$$

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

STEP 7: *Calculate the distance of each alternative from FPIS and FNIS.*

The distance (d_1^+, d_1^-) of each weighted alternative $i = 1, 2, \ldots m$ from the FPIS and FNIS is computed as follows.

$$d_1^+ = \sum_{j-1}^{n} dv(\tilde{v}_{ij}, \ \tilde{v}_j^*), \quad i = 1, 2, \ldots, m \tag{10}$$

$$d_1^- = \sum_{j-1}^{n} dv(\tilde{v}_{ij}, \ \tilde{v}_j^-), \quad i = 1, 2, \ldots, m \tag{11}$$

STEP 8: *Calculate the closeness coefficient (CC_i) of each alternative.*

The closeness coefficient CC_i represents the distances to the fuzzy positive ideal solution (A^*) and the fuzzy negative ideal solution (A^-) simultaneously. The closeness coefficient of each alternative is calculated as follows:

$$CC_i = \frac{d_1^-}{d_1^- + d_1^+} \tag{12}$$

STEP 9: *Rank the alternatives.*

In this step, the different alternatives are ranked according to the closeness coefficient (CC_i) in decreasing order.

3.3. Proposed decision-support methodology for risk management in emergency supply chains

Figure 1 illustrates the decision-support methodology for managing risks in emergency supply chains. This methodology comprises four phases and is discussed below.

Phase 1: Identification of risk factors in emergency supply chains

A thorough literature review is conducted to identify risk factors that can disrupt emergency supply chains and develop an initial risk taxonomic diagram to illustrate a proposed risk classification model. Subsequently, several experts with extensive field experience are approached to confirm the validity of these risk factors and reveal others that have been ignored. A final hierarchical structure will be developed.

Phase 2: Calculate the weight of risk factors in the emergency supply chain by fuzzy AHP.

The weights of the emergency supply chain risk factors is determined using the fuzzy AHP technique after the risk taxonomy has been established. Using the scale presented in Table 3, a comparison matrix of experts' ratings is built in order to obtain weights for each criterion. Next, the aggregated matrix is determined by calculating the geometric mean of the numbers obtained from their evaluation. Finally, priority weights for each risk factor is determined using this matrix, as explained above.

Phase 3: Identification of strategies for risk mitigation in emergency supply chains

After determining the relative importance of potential risk factors in emergency supply chains, the study then identifies strategies that can be incorporated to minimise the effects of these risks. An exhaustive literature review can reveal the risk mitigation strategies currently implemented. Next, another group of experts is assembled to assess the efficacy of various emergency supply chain risk mitigation strategies. Finally, a decision framework is established with the overarching goal at the top, followed by the primary types of risk, then the factors contributing to those risks, and finally, the risk mitigation strategies.

Phase 4: Prioritization of strategies for risk mitigation in emergency supply chains

Fuzzy TOPSIS is used to evaluate and rank the risk mitigation strategies for effective emergency supply chains. Experts are required to provide subjective judgements on the risk mitigation strategies based on the most critical risk factors using the linguistic scale presented in Table 4. Fuzzy TOPSIS's values CC_i will be used to determine the ultimate order of these strategies.

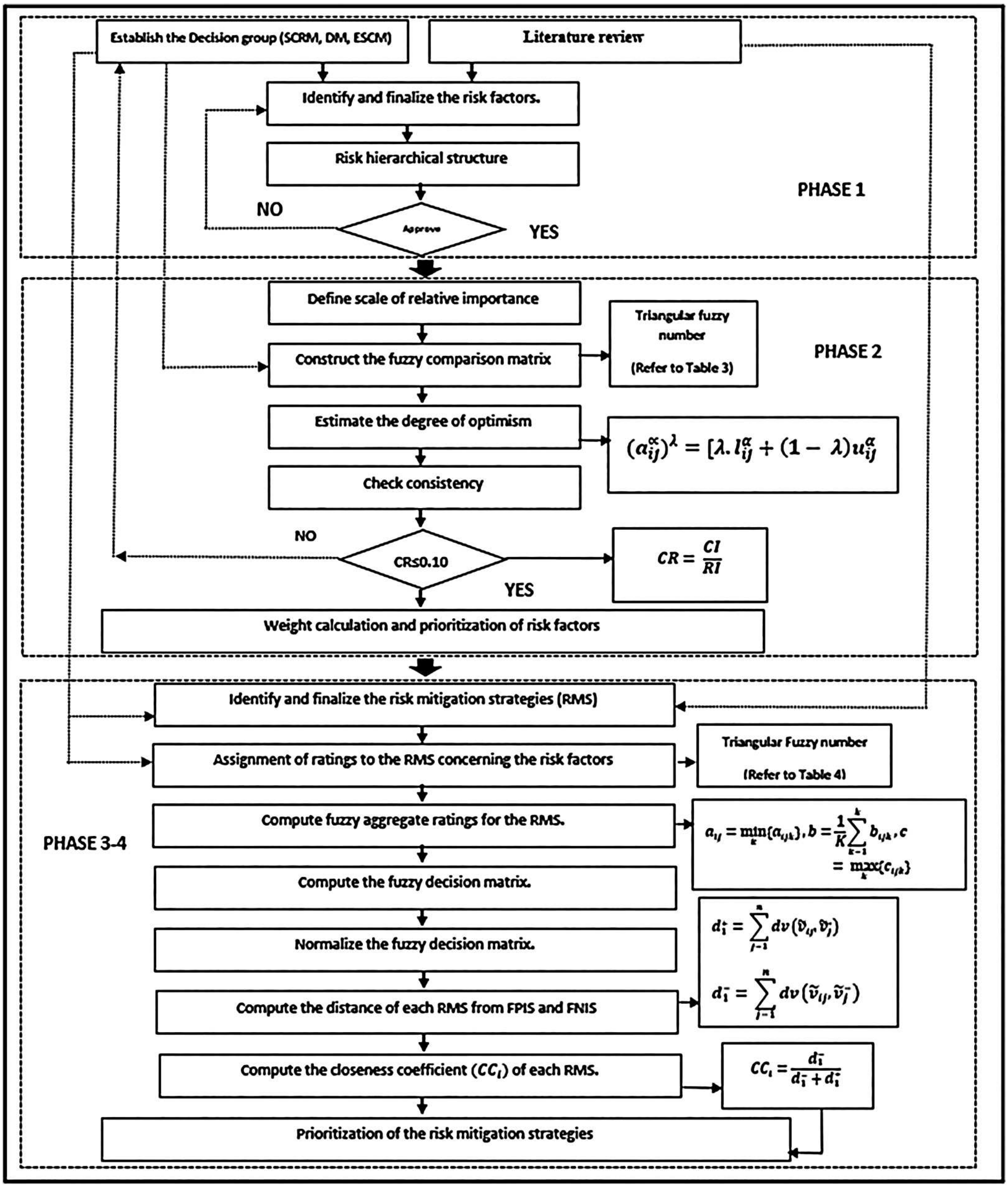

Figure 1. Decision-support methodology for risk mitigation in emergency supply chains.

4. Application of the proposed framework

4.1. Problem description

When responding to natural disasters, relief organisations frequently must carry out logistics and supply chain operations in highly unstable environments. Additionally, these organisations encounter a variety of risks and uncertainties when transporting, storing, and delivering essential supplies. There have not been many studies done on risk management in emergency supply chains, and more specifically, clear categories of risks and uncertainties experienced along emergency supply chains and mitigation strategies currently implemented still need to be empirically established and tested (L'Hermitte et al. 2015). In order to effectively manage supply chain risks, it is necessary first to identify risk events, then evaluate the probability and severity of these events, and finally devise preventative and corrective measures. (Chukwuka et al. 2023). To be successful, relief organisations must be able to respond quickly and creatively to changes in demand, supply, and operational processes. (Balcik and Beamon 2008). To accomplish this, one must plan, have the necessary resources at the ready, and be able to adjust to a variety of local circumstances while maintaining high-quality operations quickly and effectively. Several studies (L'Hermitte et al. 2015) contend that the efficiency and efficacy of an emergency supply chain are proportional to the chain's adaptability and responsiveness to external disturbances. Only adaptable (Blecken et al. 2009; Merminod et al. 2009; Oloruntoba and Gray 2009) and cost-effective delivery networks can accomplish this (Jahre, Pazirandeh, and Wassenhove 2016a; McLanchlin, Larson, and Khan 2009; Pettit and Beresford 2009).

4.2. Case analysis

Phase 1: Identification of the risk factors in emergency supply chains.

The risk factors that are likely to disrupt the effective performance of emergency supply chains were identified and adopted from the study conducted by the authors (Chukwuka et al. 2023).

Phase 2: Calculating the weight of the risk factors in emergency supply chains using fuzzy AHP.

Similarly, the analysis process of weight calculation for these risk factors in emergency supply chains has been computed by the authors (Chukwuka et al. 2023), and the results are presented in Table 5. For further analysis, the top 10 risk factors are utilised.

Phase 3: Identification of strategies for risk mitigation in emergency supply chains.

The next step is to consult the relevant published material to identify strategies that are presently being used. Evidence of several risk mitigation strategies was found through a literature review. A

Table 5. Final weights of risk factors in emergency supply chains.

Main category		Sub-category		Risk type		Specific risk factors		Global weight	Rank
Internal	0.502	Demand	0.331	Forecast	0.494	R1	0.507	0.041742332	9
						R2	0.493	0.040589684	10
				Inventory	0.506	R3	1	0.084331984	4
		Supply	0.348	Supplier	0.332	R4	0.356	0.020652674	15
						R5	0.334	0.019376385	17
						R6	0.31	0.01798407	19
						R7	0.341	0.019723248	13
				Procurement	0.334	R8	0.334	0.019318372	16
						R9	0.325	0.018797817	22
						R10	0.347	0.020010013	14
				Quality	0.333	R11	0.329	0.01897203	18
						R12	0.324	0.018683701	20
				Transportation	0.259	R13	0.253	0.014231784	25
						R14	0.251	0.01411928	26
						R15	0.251	0.01411928	26
						R16	0.245	0.013781767	27
		Infrastructural	0.321	Warehousing	0.245	R17	0.515	0.026888671	11
						R18	0.485	0.025322341	12
				Systems	0.25	R19	0.331	0.017549366	23
						R20	0.347	0.018397674	21
						R21	0.321	0.017019173	24
External	0.498	Environmental	1	Disruption	0.246	R22	0.486	0.085677912	3
						R23	0.514	0.090614088	1
				Social	0.352	R24	0.337	0.05454345	6
						R25	0.333	0.05389605	7
						R26	0.33	0.0534105	8
				Political	0.322	R27	0.537	0.085843746	2
						R28	0.463	0.074014254	5

Source: Chukwuka et al. (2023)

detailed and meticulous literature analysis was conducted to locate current supply chain strategies for mitigating risk was conducted. In particular, and building off Jahre's (2017) work, the review focused on articles that detailed in-depth case studies of relief organisations. Furthermore, the study moved to review several official documents from various bodies, including '*Global Humanitarian Overview 2022', 'DG ECHO Thematic Policy Document', 'Evaluation of Humanitarian Logistics within EU Civil Protection, 2013-2017', 'Supply Chain Expenditure & Preparedness Investment Opportunities in the Humanitarian Context, 2017', 'Emergency Supply Prepositioning Strategy, ESUPS, NEPAL, Country-Wide Analysis of Prepositioned Relief Items, 2020', 'Global Logistics Cluster, Delivery in a Moving World, 2016',* etc. The primary benefit of documentary research is that it allows researchers to gain access to data that would be difficult to acquire through more traditional methods, such as interviews with subjects who are hard to locate or who are hesitant to participate in a formal study. At the end of the first phase of empirical investigations, the study uncovered twelve risk mitigation strategies currently implemented in emergency supply chains including strategic stock, prepositioning of resources, postponement, collaboration and coordination, flexible supply base, flexible transportation, flexible supply contracts, centralisation, logistics outsourcing, decision policies, risk awareness/ knowledge management, and cash-based interventions.

Although explored in literature, more inquiry is required to validate these strategies and further uncovers others omitted. Several experts were contacted to participate in this stage of the research, however, only five returned a positive response. Table 6 presents a committee consisting of five experts to evaluate the different strategies for risk mitigation in emergency supply chains. This evaluation was carried out based on the top 11 risk factors from the previous analysis. Analysing all potential risks can be time-consuming and resource intensive. Focusing on the most critical risk factors allows for a deeper analysis within a set timeframe. Moreover, analysing a smaller number of risk factors allows for the development of more concrete mitigation strategies. Semi-structured interviews (3) and high-level surveys (2) were used throughout this process of assessment. The duration of each discussion was forty-five minutes.

After completing this empirical study, only eight risk mitigation techniques were selected for in-depth evaluation due to the limited amount of data available (see Figure 2). While every strategy is ultimately helpful, emergency relief operations are currently struggling to make the most of postponement, centralisation, decision policies/procedures, and cash-based methods. The framework of the decision hierarchy is presented in Figure 3.

Phase 4: Evaluation of the risk mitigation strategies in emergency supply chains

Several channels, including LinkedIn and the Humanitarian Logistics Association (HLA), were used to contact various experts in the field. Thirteen experts agreed to participate in the survey. Some showed interest but provided a few reasons why they would not take part in the survey.

The survey via questionnaire was carried out over five weeks, beginning on November 9th and ending on December 9th, 2022. To complete the survey, a variety of experts who each possess their unique level of expertise and abilities as well as a considerable degree of knowledge in the fields of emergency supply chain management, disaster management, and supply chain risk management were contacted. The eligible experts were contacted and asked to confirm that they would be willing to participate in the survey. Therefore, after receiving a response indicating that they were interested in participating, the questionnaire was sent to the expert. In addition, the survey was completed by both academics and practitioners who are considered to be authorities in their

Table 6. Expert profile.

Expert	Position	Method	Experience
Expert 1	Senior operations consultant	Face-to-Face interview (Ms-Teams)	+30years
Expert 2	Director of Logistics	Face-to-Face interview (Ms-Teams)	+30years
Expert 3	Professor	Face-to-Face interview (Skype)	+20 years
Expert 4	Professor	Questionnaire	+20 years
Expert 5	Consultant	Questionnaire	+20 years

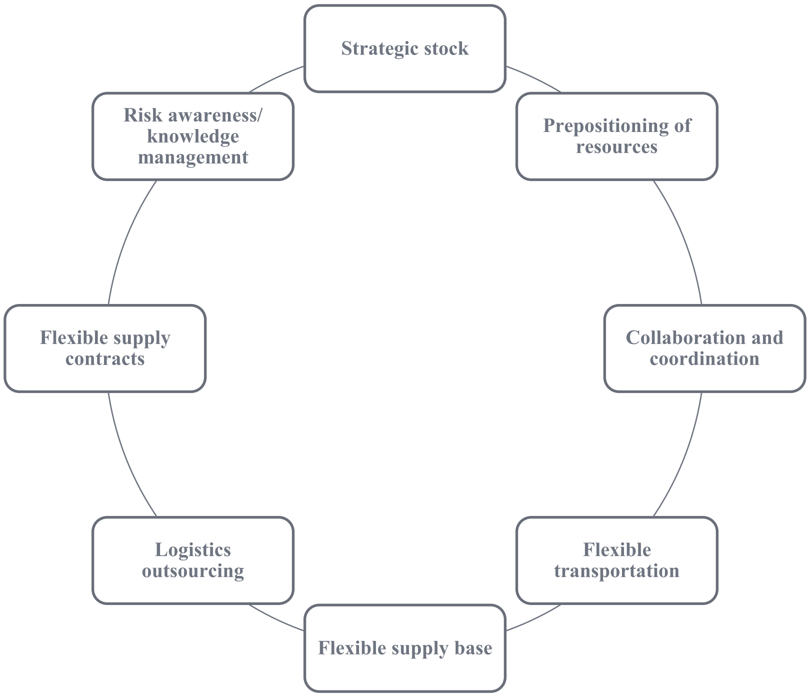

Figure 2. Risk mitigation strategies in emergency supply chains.

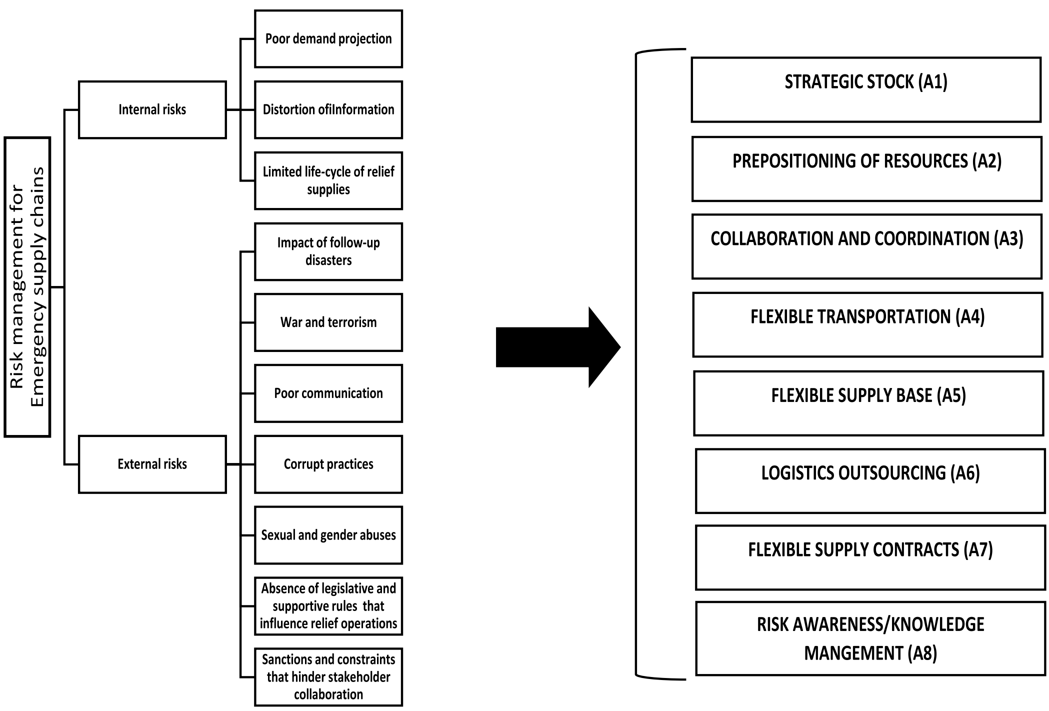

Figure 3. Decision hierarchy for prioritising risk mitigation strategies in emergency supply chains.

fields. The developed questionnaire is web-based and can be accessed easily through an online link. At the end of the survey, four experts did begin the survey but did not complete it. Only nine responses were completed and accepted for further analysis. The return rate of the survey is acceptable since relevant information was received from experts with sufficient knowledge and expertise. Using the fuzzy linguistic scale in Table 7, nine experts were asked to construct a fuzzy evaluation matrix. The details of these experts are presented in Table 8. This matrix is constructed by comparing the risk mitigation strategies under each risk factor respectively. The linguistic terms are then converted to corresponding triangular fuzzy numbers, which will be used to construct the fuzzy evaluation matrix. Due to space limitations, the linguistic evaluation matrix and fuzzy evaluation matrix of three experts are only given in Tables 9 and 10. Aggregated fuzzy weights of the risk mitigation are computed using Equation 2 and presented in Table 11. The objective of this research is to minimise the effects of risks in emergency supply chains. Hence, all the risk factors are classed as cost criteria, and normalisation is done using Equation 6. Table 12. presents the fuzzy normalised matrix, and Table 13 presents the weighted normalised matrix, which has been computed using the priority weights of the risk factors initially calculated.

Since all the risk factors are classed as cost criteria, the fuzzy positive-ideal solution ($FPIS,\ A^*$) and fuzzy negative ideal solution ($FNIS,\ A^-$) as $\tilde{V}^* = (0, 0, 0)$ and $\tilde{V}^* = (1, 1, 1)$ for all these risk

Table 7. Fuzzy linguistic variable for strategies rating.

Linguistic terms	L	M	U
Very Poor	1	1	3
Poor	1	3	5
Medium	3	5	7
Good	5	7	9
Very Good	7	9	11

Table 8. Profile of survey experts.

Experts	Affiliated Organisation	Job description	Years of work experience	Relief operation participated	Organisational size
1	Relief organisation	Supply chain and logistics consultant	>20	Yes, I have participated in several relief operations	400
2	Non-governmental organisation	Project coordinator	>20	Yes, Flood,2000, SIDR-2007, AILA,2009; Water Logging, 2011; Cyclone Bulbul, 2019; Cyclone Foni, 2019, Cyclone AMPHAN, 2020; Cyclone YAAS, 2021, Cyclone Shitrang, 2022; Cyclone, YAAS	650
3	Human research institute	Researcher	6–10	Yes, in my previous position (4 years with an NGO), I helped multiple field positions.	>60k
4	Self-employed	Consultant	>20	Yes – various since 1995	1
5	Relief organisation	Relief Coordinator	11–15	Yes, the Distribution of NFIs	180
6	Relief organisation	Operations and Programmes coordinator	11–15	During my 13 years of experience, I participated in several relief operations, be it country level or at the international level.	>100k
7	Non-governmental organisation	Regional logistics manager	11–15	Yes	5000
8	Non-governmental organisation	Emergency, preparedness, and response specialist	16–20	Yes	80
9	Non-governmental organisation	Logistic manager	11–15	Lombok Earthquake Palu and Donggala Earthquake and Tsunami, Sunda Strait Tsunami:	50

Table 9. Linguistic scale evaluation for a risk factor (war and terrorism) (3 experts).

Risk Factor	Alternative	Experts		
		E1	E2	E3
War and terrorism	Strategic Stock	VG	G	M
	Prepositioning Resources	VG	M	M
	Collaboration and Coordination	VG	G	VG
	Flexible Transportation	G	VG	VG
	Flexible Supply Base	G	M	VG
	Logistics Outsourcing	VG	M	*P*
	Flexible Supply Contracts	G	*P*	*P*
	Risk Awareness/ Knowledge management	VG	M	G

Table 10. Fuzzy evaluation matrix for risk mitigation strategies (3 experts).

Risk Factor	Alternative	Experts		
		E1	E2	E3
War and terrorism	Strategic Stock	(7,9,11)	(5,7,9)	(3,5,7)
	Prepositioning Resources	(7,9,11)	(3,5,7)	(3,5,7)
	Collaboration and Coordination	(7,9,11)	(5,7,9)	(7,9,11)
	Flexible Transportation	(5,7,9)	(7,9,11)	(7,9,11)
	Flexible Supply Base	(5,7,9)	(3,5,7)	(7,9,11)
	Logistics Outsourcing	(7,9,11)	(3,5,7)	(1,3,5)
	Flexible Supply Contracts	(5,7,9)	(1,3,5)	(1,3,5)
	Risk Awareness/ Knowledge management	(7,9,11)	(3,5,7)	(5,7,9)

factors. Then, compute the distance d_v of each alternative from FPIS (A^*) and FNIS (A^-) using the Equation 10 and Equation 11

For example, for strategy, S1 with respect to risk factor, R1:

$$d(A_1, A^*) = \sqrt{\frac{1}{3}\ (0 - 0.008)^2 + (0 - 0.013)^2 + (0 - 0.030)^2}$$

$$d(A_1, A^*) = 0.01943$$

$$d(A_1, A^-) = \sqrt{\frac{1}{3}\ (1 - 0.008)^2 + (1 - 0.013)^2 + (1 - 0.030)^2}$$

$$d(A_1, A^-) = 0.98305$$

Similarly, calculations are done for all alternatives with respect to all criteria. At the end of the calculations, the cumulative distances of d_1^* and d_1^- are also computed. For alternative A1, the cumulative distances from the positive ideal solution, $d_1^* = 0.32576$ and negative ideal solution, $d_1^- = 9.7618$. Tables 14 and 15 present the values of FPIS and FNIS for all alternatives and criteria. The closeness coefficient represents the distance between the fuzzy positive ideal solution and the fuzzy negative ideal solution.

Using Equation 12

$$CC_i = \frac{d_1^-}{d_1^- + d_1^+}$$

For example, the CC_i for strategy can be computed as follows:

$$CC_i = \frac{9.7618}{(0.32576 + 9.7618)} = 0.967706759$$

Table 11. Aggregate fuzzy decision matrix for risk mitigation strategies.

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
S1	(3,6.778,11)	(1,6.333,11)	(3,7.444,11)	(1,6.111,11)	(1,5.667,11)	(1,5.000,11)	(1,4.556,11)	(1,4.778,11)	(1,6.333,11)	(1,5.222,11)
S2	(3,7.222,11)	(1,7.000,11)	(3,7.889,11)	(1,6.556,11)	(1,6111,11)	(1,5.222,11)	(1,5.000,11)	(1,5.444,11)	(1,5.444,11)	(1,5.222,11)
S3	(5,8.111,11)	(3,7.889,11)	(5,8.333,11)	(3,8.333,11)	(1,7.000,11)	(1,7.222,11)	(1,6.556,11)	(1,7.000,11)	(1,7.667,11)	(1,7.889,11)
S4	(5,7.889,11)	(3,6.333,11)	(5,8.111,11)	(3,7.000,11)	(1,5.667,11)	(1,5.889,11)	(1,4.333,11)	(1,5.000,11)	(1,7.000,11)	(1,5.889,11)
S5	(3,7.222,11)	(1,7.000,11)	(3,7.667,11)	(3,7.000,11)	(1,5.889,11)	(1,6.778,11)	(1,4.556,9)	(1,5.000,11)	(1,7.222,11)	(1,5.889,11)
S6	(1,6.556,11)	(1,7.222,11)	(1,6.778,11)	(3,7.222, 11)	(1,5.444,11)	(1,6.778,11)	(1,5.222,11)	(1,5.000,11)	(1,6.333,11)	(1,6.111,11)
S7	(1,6.111,11)	(1,6.778,11)	(1,7.000,11)	(3,7.444,11)	(1,6.333,11)	(1,6.556,11)	(1,5.889,11)	(1,4.778,11)	(1,7.222,11)	(1,6.111,11)
S8	(3,7.6667,11)	(1,7.000,11)	(1,7.222,11)	(1,6.556,11)	(1,6.556,11)	(1,7.444,11)	(1,5.889,11)	(1,7.444,11)	(1,6.111,11)	(1,7.444,11)

Table 12. Normalised fuzzy decision matrix for risk mitigation strategies.

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
S1	(0.090,0.148,0.333)	(0.090,0.158,1)	(0.090,0.134,0.333)	(0.090,0.164,1)	(0.090,0.176,1)	(0.090,0.200,1)	(0.090,0.219,1)	(0.090,0.209,1)	(0.090,0.158,1)	(0.090,0.191,1)
S2	(0.090,0.138,0.333)	(0.090,0.143,1)	(0.090,0.127,0.333)	(0.090,0.153,1)	(0.090,0.164,1)	(0.090,0.191,1)	(0.090,0.200,1)	(0.090,0.184,1)	(0.090,0.184,1)	(0.090,0.191,1)
S3	(0.090,0.123,0.200)	(0.090,0.127,0.333)	(0.090,0.120,0.200)	(0.090,0.120,0.333)	(0.090,0.143,1)	(0.090,0.138,1)	(0.090,0.153,1)	(0.090,0.143,1)	(0.090,0.130,1)	(0.090,0.127,1)
S4	(0.090,0.127,0.200)	(0.090,0.158,0.333)	(0.090,0.123,0.200)	(0.090,0.143,0.333)	(0.090,0.176,1)	(0.090,0.170,1)	(0.090,0.231,1)	(0.090,0.200,1)	(0.090,0.143,1)	(0.090,0.170,1)
S5	(0.090,0.138,0.333)	(0.090,0.143,1)	(0.090,0.130,0.333)	(0.090,0.143,0.333)	(0.090,0.170,1)	(0.090,0.148,1)	(0.111,0.219,1)	(0.090,0.200,1)	(0.090,0.138,1)	(0.090,0.170,1)
S6	(0.090,0.153,1)	(0.090,0.138,1)	(0.090,0.148,1)	(0.090,0.138,0.333)	(0.090,0.184,1)	(0.090,0.148,1)	(0.090,0.191,1)	(0.090,0.200,1)	(0.090,0.158,1)	(0.090,0.164,1)
S7	(0.090,0.164,1)	(0.090,0.148,1)	(0.090,0.143,1)	(0.090,0.134,0.333)	(0.090,0.158,1)	(0.090,0.153,1)	(0.090,0.170,1)	(0.090,0.209,1)	(0.090,0.138,1)	(0.090,0.164,1)
S8	(0.090,0.130,0.333)	(0.090,0.143,1)	(0.090,0.138,1)	(0.090,0.153,1)	(0.090,0.153,1)	(0.090,0.134,1)	(0.090,0.170,1)	(0.090,0.134,1)	(0.090,0.164,1)	(0.090,0.134,1)

Table 13. Weighted normalised fuzzy decision matrix for risk mitigation strategies.

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
S1	(0.008,0.013,0.030)	(0.008,0.014,0.086)	(0.008,0.011,0.029)	(0.008,0.014,0.084)	(0.007,0.013,0.074)	(0.005,0.011,0.0545)	(0.005,0.012,0.0539)	(0.005,0.011,0.0534)	(0.004,0.007,0.0417)	(0.004,0.008,0.0406)
S2	(0.008,0.013,0.030)	(0.008,0.012,0.086)	(0.008,0.011,0.029)	(0.008,0.013,0.084)	(0.007,0.012,0.074)	(0.005,0.010,0.0545)	(0.005,0.011,0.0539)	(0.005,0.010,0.0534)	(0.004,0.008,0.0417)	(0.004,0.008,0.0406)
S3	(0.008,0.011,0.018)	(0.008,0.011,0.029)	(0.008,0.010,0.017)	(0.008,0.010,0.028)	(0.007,0.011,0.074)	(0.005,0.008,0.0545)	(0.005,0.008,0.0539)	(0.005,0.008,0.0534)	(0.004,0.005,0.0417)	(0.004,0.005,0.0406)
S4	(0.008,0.012,0.018)	(0.008,0.014,0.029)	(0.008,0.011,0.017)	(0.008,0.012,0.028)	(0.007,0.013,0.074)	(0.005,0.009,0.0545)	(0.005,0.012,0.0539)	(0.005,0.011,0.0534)	(0.004,0.006,0.0417)	(0.004,0.007,0.0406)
S5	(0.008,0.013,0.030)	(0.008,0.012,0.086)	(0.008,0.011,0.029)	(0.008,0.012,0.028)	(0.007,0.013,0.074)	(0.005,0.008,0.0545)	(0.006,0.012,0.0539)	(0.005,0.011,0.0534)	(0.004,0.006,0.0417)	(0.004,0.007,0.0406)
S6	(0.008,0.014,0.091)	(0.008,0.012,0.086)	(0.008,0.013,0.086)	(0.008,0.012,0.028)	(0.007,0.014,0.074)	(0.005,0.008,0.0545)	(0.005,0.010,0.0539)	(0.005,0.011,0.0534)	(0.004,0.007,0.0417)	(0.004,0.007,0.0406)
S7	(0.008,0.015,0.091)	(0.008,0.013,0.086)	(0.008,0.012,0.086)	(0.008,0.011,0.028)	(0.007,0.012,0.074)	(0.005,0.008,0.0545)	(0.005,0.009,0.0539)	(0.005,0.011,0.0534)	(0.004,0.006,0.0417)	(0.004,0.007,0.0406)
S8	(0.008,0.012,0.030)	(0.008,0.012,0.086)	(0.008,0.012,0.086)	(0.008,0.013,0.084)	(0.007,0.011,0.074)	(0.005,0.007,0.0545)	(0.005,0.009,0.0539)	(0.005,0.011,0.0534)	(0.004,0.007,0.0417)	(0.004,0.005,0.0406)
W	0.0906	0.0858	0.0857	0.0843	0.074	0.0545	0.0539	0.0534	0.0417	0.0406

Table 14. Fuzzy positive ideal solution (FPIS) values.

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	d_1^*
S1	0.01943	0.05052	0.01849	0.04938	0.04357	0.03223	0.03201	0.03161	0.02452	0.024	0.32576
S2	0.01943	0.05035	0.01849	0.04929	0.04347	0.03212	0.03189	0.0315	0.02462	0.024	0.32516
S3	0.01303	0.01849	0.01229	0.01778	0.04338	0.03193	0.03159	0.03131	0.02436	0.02373	0.24789
S4	0.01332	0.01916	0.01257	0.01818	0.04357	0.03202	0.03201	0.03161	0.02443	0.0239	0.25077
S5	0.01943	0.05035	0.01849	0.01818	0.04357	0.03193	0.03207	0.03161	0.02443	0.0239	0.29396
S6	0.05336	0.05035	0.05043	0.01818	0.04367	0.03193	0.03178	0.03161	0.02452	0.0239	0.35973
S7	0.05345	0.05043	0.05035	0.01797	0.04347	0.03193	0.03168	0.03161	0.02443	0.0239	0.35922
S8	0.01922	0.05035	0.05035	0.04929	0.04338	0.03186	0.03168	0.03161	0.02452	0.02373	0.35599

Table 15. Fuzzy negative ideal solution (FNIS) values.

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	d_1^-
S1	0.98305	0.96465	0.98404	0.96528	0.96914	0.97675	0.97661	0.9771	0.98258	0.9826	9.7618
S2	0.98305	0.96533	0.98404	0.96562	0.96948	0.97709	0.97694	0.97744	0.98225	0.9826	9.76384
S3	0.98768	0.98404	0.98834	0.98471	0.96982	0.97776	0.97796	0.97812	0.98326	0.98361	9.8153
S4	0.98734	0.98304	0.98801	0.98404	0.96914	0.97742	0.97661	0.9771	0.98292	0.98294	9.80856
S5	0.98305	0.96533	0.98404	0.98404	0.96914	0.97776	0.97627	0.9771	0.98292	0.98294	9.78259
S6	0.96308	0.96533	0.96499	0.98404	0.9688	0.97776	0.97728	0.9771	0.98258	0.98294	9.7439
S7	0.96273	0.96499	0.96533	0.98437	0.96948	0.97776	0.97762	0.9771	0.98292	0.98294	9.74524
S8	0.98338	0.96533	0.96533	0.96562	0.96982	0.9781	0.97762	0.9771	0.98258	0.98361	9.74849

Table 16. Fuzzy-TOPSIS results.

	d_1^+	d_1^-	CC_i	Rank
S1	0.32576	9.76180	0.967706759	5
S2	0.32516	9.76384	0.967708390	4
S3	0.24789	9.81530	0.975366580	1
S4	0.25077	9.80856	0.975070904	2
S5	0.29396	9.78259	0.970827316	3
S6	0.35973	9.74390	0.964395964	8
S7	0.35922	9.74524	0.964449362	7
S8	0.35599	9.74849	0.964769092	6

Similar calculations are done for all alternatives before proceeding to the final step. Table 16 presents the CC_i values for all risk mitigation strategies. Based on the CC_i value, the strategies are ranked.

4.3. Results and discussion

This study investigates the challenge of selecting appropriate risk mitigation strategies for effective emergency supply chain operations. The proposed methodology, incorporating a literature review and expert opinion, aims to simplify this process. The first objective of the study focuses on identifying the most prevalent risk factors disrupting emergency supply chains. Literature review reveals that, compared to business supply chains, emergency stakeholders face a greater vulnerability to external risks (Day et al. 2012; Jahre 2017). The second objective utilises expert opinion and literature review to identify currently implemented risk mitigation strategies. The research acknowledges the global trend of businesses enhancing their responsiveness to disruptions (unspecified source). However, vulnerabilities expose global supply chains to diverse risks, manifesting in various forms and impacting different chains uniquely (unspecified source). Abidi, Leeuw, and Klumpp (2015) emphasises the criticality of effective emergency supply chains in disaster relief, highlighting poor management as a significant factor hindering relief efforts. The analysis identified eight risk mitigation strategies. Fuzzy TOPSIS was then employed to evaluate and rank these strategies considering the most prevalent emergency supply chain risk factors.

Contrary to findings suggesting strategic stockpiling as the most common mitigation strategy (Aghajani and Torabi 2020; Jahre 2017), this study prioritises collaboration and coordination, flexible transportation, and flexible supply bases for stakeholders developing strategic plans for optimal emergency supply chains. Collaboration and coordination, identified as the most important strategy, is considered the core of supply chain management (Akhtar, Marr, and Garnevska 2012). Defined as the 'relationships and interactions amongst different actors operating within the emergency relief environment' (Balcik et al. 2010), it plays a vital role throughout emergency relief activities. Fragmented efforts often lead to duplication of resources and inefficiencies (Chong et al. 2019; Dolinskaya, Besiou, and Guerrero-Garcia 2018). Relief actors frequently lack the necessary resources to respond independently, necessitating collaboration to support vulnerable populations (Balcik et al. 2010; Moshtari 2016; Sigala and Wakolbinger 2019). Collaboration fosters effective responses by facilitating understanding and addressing operational actions. Building trust among actors is crucial for this strategy's success (Ahmed et al. 2019). However, Moshtari (2016) highlights the challenges faced by relief organisations in achieving desired outcomes due to a lack of collaboration under uncertain conditions. Despite potential costs and delays, collaboration and coordination are considered essential for maximising scarce resources and saving lives.

Flexible transportation plans emerge as the second priority. Transportation is a critical yet challenging aspect of disaster relief operations (Ngwenya and Naude 2016). Speed is paramount, necessitating exploration of diverse options to deliver supplies rapidly within budgetary constraints. Utilising multiple modes of transportation (road, rail, air, water) broadens decision-making options (unspecified source). However, arranging transportation, particularly for 'last mile' deliveries in volatile environments, poses difficulties for relief organisations (Balcik and Beamon 2008). A flexible strategy is required to enhance response capabilities under risk and uncertainty. Disaster relief planning must account for potential risks and available transportation options, considering diverse modes for both transportation and evacuation (Maghfiroh and Hanaoka 2020). Each mode offers unique advantages in terms of cost, capacity, and timeliness. Ultimately, the chosen mode should be suitable for the disaster area, operational conditions, and budget constraints (Yadav and Barve 2015). Route selection may also be influenced by the chosen mode, delivery timeframe, and quantity of supplies.

Flexible supply bases represent the third most critical strategy. Suppliers are essential for rapid and effective emergency responses. Multiple sourcing strategies (utilising two or more suppliers) can mitigate or eliminate disruptions within the emergency relief supply chain (Torabi et al. 2018). While single sourcing offers cost benefits (lower supply management costs, quantity discounts), it increases vulnerability to demand fluctuations and catastrophic disruptions (Tang 2007). A flexible sourcing strategy empowers the supply chain to overcome these challenges and ensures the availability of essential supplies to protect populations and prevent further casualties.

The study concludes that **logistics outsourcing** is the least prioritised strategy for mitigating emergency supply chain risks. While logistics service providers (LSPs) play a significant role in emergency relief efforts (Sánchez Gil and McNeil 2015; Vega and Roussat 2015; Cozzolino, Wankowicz, and Massaroni 2017; Baharmand, Comes, and Lauras 2017), findings align with Bealt, Fernández Barrera, and Mansouri (2016) who suggest that only a small portion of stakeholders find partnerships with LSPs to be fruitful.

4.3.1. Sensitivity analysis

In order to assess how sensitive the ranking of alternatives is to shifts in the relative importance of various barriers; a sensitivity analysis is carried out. There was a total of thirteen experiments carried out. The results of the experiment are presented in Table 17, which can be found here. It is clear from looking at Table 17 that during the first ten experiments, the weight of each barrier was gradually made progressively heavier one at a time until they were all at the same level. For instance, in experiment 1, the weight of criteria (R1) = 0.50, and the weight of the remaining nine criteria (R2–R10) are presumed to be of equal value; as a result, they are allotted the same weight, which is 0.25. Experiment 11 finds that the total weight of all the barriers amounts to 0.04. In experiment 12, the weight of the barriers (R1–R5) was equal to 0.125, and the weight of the other obstacles was 0. The changes that occur in the final ranking of the risk mitigation strategies for emergency supply chains are depicted in Figure 4. These changes take place when the weights of the barriers are altered.

Table 17 and Figure 4 illustrate the fact that, out of a total of 13 experiments, the alternative A3 (collaboration and coordination) received the highest score, followed by A4, A5, A2, A1, A8, A7 and A6. The ranking of the alternatives remained the same in eleven experiments (Expt. 1,2,3,5,6,7,8,9,10,11,12). In experiment 4, the alternatives A7 and A6 moved to fourth and fifth place and A2, A1, and A8 emergency as the least three alternatives. In experiment 13, alternative A8, A7, A6 and A5 follows alternative A3 respectively. A4, A2 and A1 emerged as the least three strategies. When the weights of the criteria are changed, the rankings of other alternatives shift considerably. As a result, the ranking of supply chain strategies for risk management in emergency supply chains is relatively sensitive to the weights of the criteria.

5. Implications

Despite its significance, the management of risks in emergency supply chains has not been given adequate attention. (Jahre 2017). Relief organisations encounter micro and macro risks while planning for and addressing disasters. In contrast to commercial supply chains, these organisations are comparatively more susceptible to macro risks since their supply chains are established and function in regions that have been impacted and are prone to further disasters. (Day et al. 2012). Therefore, it is crucial to make adequate preparations for potential disruptions. Numerous risk management strategies have been proposed in scholarly literature pertaining to emergency supply

Table 17. Experiments for sensitivity analysis.

Ex. No	Definition	A1	A2	A3	A4	A5	A6	A7	A8
1	R1=0.50, R2-R10=0.25	0.871035087	0.871391442	0.894205197	0.893120028	0.88844624	0.863359132	0.86351156	0.863771791
2	R2=0.50, R1, R3-R10=0.25	0.862888097	0.863245841	0.89261141	0.891324057	0.871729584	0.855141091	0.85524899	0.855668682
3	R3=0.50, R1-R2, R4-R10=0.25	0.871132207	0.87147954	0.894190397	0.893060162	0.880024296	0.855110814	0.85526426	0.85568365
4	R4=0.50, R1-R3, R5-R10=0.25	0.862869015	0.863215495	0.892647188	0.891412495	0.879952648	0.863220032	0.86337901	0.855637938
5	R5=0.50, R1-R4, R6-R10=0.25	0.862829679	0.863180851	0.8842035	0.88298267	0.871646511	0.85499294	0.85521765	0.855637938
6	R6=0.50, R1-R5, R7-R10=0.25	0.862746355	0.863090259	0.884217567	0.883001846	0.871714812	0.855110814	0.85523346	0.85569543
7	R7=0.50, R1-R6, R8-R10=0.25	0.86267604	0.863058322	0.884174509	0.882788218	0.871423093	0.854968422	0.85517864	0.855583211
8	R8=0.50, R1-R7, R9-R10=0.25	0.862713524	0.8631145	0.8842035	0.882901934	0.871544792	0.854936143	0.8550413	0.85569543
9	R9=0.50, R1-R8, R10=0.25	0.862888097	0.8631145	0.884239477	0.883083094	0.871744077	0.85507946	0.85527925	0.855602879
10	R10=0.50, R1-R9=0.25	0.862778324	0.863090259	0.884247504	0.883001846	0.871646511	0.855060133	0.85519834	0.85569543
11	R1-R10=0.04	0.97952876	0.979572134	0.983181298	0.983025505	0.981053058	0.978128115	0.97814619	0.978197434
12	R1-R5=0.125, R6-R10=0	0.945978203	0.946167916	0.967757538	0.967334621	0.955095573	0.937160384	0.93721319	0.937299651
13	R1-R5=0, R6-R10=0.125	0.927729127	0.92782458	0.928526489	0.927905602	0.92797802	0.928074239	0.928144227	0.92841088

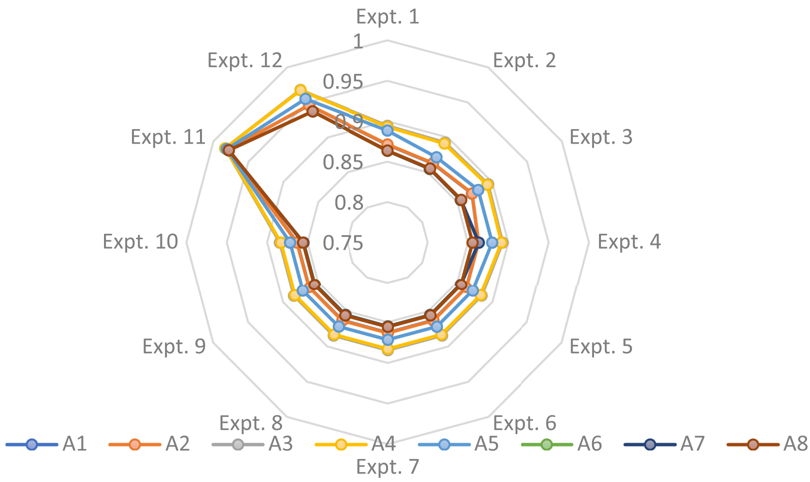

Figure 4. Result of sensitivity analysis (CCi scores).

chains. However, a significant portion of this evidence is based on anecdotal accounts, and there exists a dearth of understanding regarding the adoption of these strategies. Hence, the present study aims to bridge this research gap by proposing a risk management framework for emergency supply chains. The risks encountered by relief organisations during emergency response operations may vary based on a range of factors, including the nature, magnitude, and geographical location of the catastrophe, as well as the prevailing conditions in the affected areas (Balcik and Beamon 2008). The potential risks associated with a particular activity or situation may change over a period and exhibit varying patterns of evolution across different geographical locations. In an environment characterised by instability, comprehending the primary risks associated with global emergency supply chains can serve to mitigate their effects (Chari, Ngcamu, and Novukela 2021). Nonetheless, the objective is not to make broad generalisations but rather to thoroughly investigate the complete range of the phenomenon (Manuj and Mentzer 2008). Several research and managerial implications result from this effort.

5.1. Research implications

This research offers a significant contribution to the existing body of knowledge on risk management within emergency supply chains (ESCs). It presents a comprehensive framework that provides valuable insights into two key areas; Risk Identification: The study facilitates the identification of risks inherent in ESC systems, enabling relief organisations to effectively manage these risks during disaster relief operations. Risk Mitigation Strategies: Empirical evidence is used to identify risk factors and develop evidence-based strategies for mitigating their impact on ESCs.

Furthermore, the research delves into the diverse perspectives of stakeholders regarding ESC risk identification and management. While existing literature explores various risk mitigation approaches, it often lacks clarity on the specific contexts where these strategies are most effective. This study aims to bridge this gap by identifying the factors that influence the adoption of specific risk mitigation strategies within ESCs. A key contribution is the introduction of a decision-support methodology that facilitates the evaluation of risk factors and mitigation strategies within a framework designed to support informed decision-making by emergency relief managers. This framework addresses a critical limitation in the current ESC and risk management literature, which is often characterised a fragmented understanding due to a focus on specific phases of the risk management process. This study advances the field of decision-making under complex uncertainty.

Additionally, it provides a practical approach for structuring risk management practices in intricate emergency response environments.

5.2. Managerial implications

This study proposes a holistic approach to emergency supply chain risk management, advocating for a contextual orientation among decision-makers. This orientation fosters a comprehensive understanding of emergency risk factors and facilitates the development of effective emergency supply chain risk management practices. Decision-makers must consider the intricate interplay of complexities and unique characteristics inherent to emergency supply chains and their operating environments. Additionally, they must account for the three fundamental stages of supply chain risk management, the diverse risk factors present, the various stakeholders involved, and the overarching objectives of the emergency supply chain. The proposed model's unique strength lies in its integration of Fuzzy Analytical Hierarchy Process (FAHP) and Fuzzy Technique for Order Performance by Similarity to Ideal Solution (FTOPSIS). This integration allows for the incorporation of decision-maker preferences during strategic ESCRM decision-making. Furthermore, the model acknowledges the inherent uncertainties associated with incomplete data. By leveraging fuzzy logic theory, the model assists relief organisations in effectively managing these uncertainties, ultimately facilitating expeditious decision-making. This research offers practical contributions through the conduct of global empirical studies. This research has resulted in the development of a resource-efficient and time-saving decision-making tool for emergency relief practitioners. The findings of this study provide stakeholders and decision-makers with the most recent data on the current landscape of global disaster management. Notably, the study investigated mitigation strategies with a proven record of practical feasibility, identified through real-world applications rather than solely from literature reviews. This enables relief organisations to utilise the proposed mitigation strategies to evaluate and potentially improve their existing risk management practices. The introduction of eight critical mitigation strategies, substantiated by data from both experts and organisational reports, enhances the preparedness of relief organisations in responding to potential risks. Finally, the established profile of emergency supply chain risks empowers stakeholders and decision-makers to proactively anticipate and address potential risk factors. While this research does not encompass every conceivable risk that could arise during emergency relief operations, it provides a thorough investigation of many critical factors. The study draws upon diverse sources such as academic literature, official reports, and the insights of practitioners in various relevant positions within the disaster management industry, offering a well-rounded and comprehensive perspective.

6. Conclusion and further research

This study assessed risk mitigation methods for emergency supply lines. Empirical research was adopted to find real-world strategies. Eight strategies were uncovered, including '*strategic stock*', '*prepositioning of resources*', '*collaboration and coordination*', '*flexible transportation*', '*flexible supply base*', '*logistics outsourcing*', '*flexible supply contracts*', and '*risk awareness/knowledge management*'. After identification, a risk mitigation strategy questionnaire survey assessed the relevance of each strategy for risk reduction in emergency supply chains. Risk management is complicated and includes ambiguity and uncertainty in decision-making. Thus, a Fuzzy TOPSIS model was created to aid risk reduction decision-making. The fuzzy method can aid decision-making in situations with unresolved issues. A3, A4, A5, A2, A1, A8, A7, and A6 are the eight strategies in descending order of priority. 'Collaboration and coordination' and 'Flexible transportation' have the best relative closeness indices and should be recommended for the design of any emergency supply chains.

This study focuses on risk management in emergency supply chains. It is imperative to comprehend that each context in which disaster relief is administered is unique and possesses distinct characteristics. The attributes mentioned above are ascertained based on the impact, magnitude, temporal occurrence, and geographical extent of the calamity. Drawing upon the findings of this study, future research endeavours ought to prioritise the exploration of diverse categories of disasters, with the aim of discerning distinctive risk factors and response strategies that are pertinent to the diverse settings in which relief operations are being executed. The provision of aid during emergencies garners the involvement of individuals from diverse professional backgrounds and geographical locations. The relief effort involves various stakeholders such as donors, the government, relief organisations, non-governmental organisations, logistics service providers, armed forces, and beneficiaries. During this study, only experienced professionals from a limited number of disciplines provided their perspectives for further analysis. Despite several endeavours, the retrieval of inputs from the donors, government, or military could not be accomplished. While the success of relief efforts cannot be guaranteed, a collaborative approach involving all actors is necessary to enhance their effectiveness. The study's scope could potentially be broadened by obtaining input from the involved sectors. Therefore, it is imperative for additional research to ensure the inclusion of all relief actors in their empirical investigations in order to augment the validity and robustness of their findings. Within the emergency supply chain, a multitude of risk factors exist. Certain risk factors were excluded from this study due to their perceived insignificance and expedience; nevertheless, they warrant attention.

Consequently, additional research may incorporate diverse risk factors inherent to the structural framework, thereby enabling the potential of acquiring more all-encompassing outcomes. Despite the challenging trade-offs that may exist between cost efficiency and flexibility, enhanced preparedness can lead to improved responsiveness. It is imperative to evaluate the advantages and disadvantages of implementing appropriate risk management mitigation measures, as the execution of any approach will require substantial expenditures. The primary objective of emergency relief endeavours should invariably be to avert loss of life. Given the financial constraints often associated with this industry, conducting further research can facilitate a thorough evaluation of costs and benefits. This analysis can then inform critical strategic decisions related to risk management within emergency supply chains.

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Ethical approval

This study has received ethical approval (21/ENR/001) from LJMU's Research Ethics Committee.

Data availability statement

The data that support the findings of this study are available from the corresponding author upon request.

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Appendix

Fuzzy logic

In many professional situations, experts are confronted with a set of alternatives they need to choose from, for example, when selecting a supplier or technology. This decision is intuitive when considering a single attribute or criterion since these experts can select the attribute with the highest relevance. When several criteria have varying degrees of importance, decision-making becomes complex and challenging for experts. Hence, formal methods are needed to ensure a structured means of decision-making. Multi-criteria decision-making (MCDM) is suitable to meet the research goal, but since emergency supply chain activities are conducted in unstable and uncertain environments, integration of fuzzy set theory can improve the decision-making process. Fuzzy set theory is a mathematical approach developed by Zadeh (1965) to deal with uncertain, imprecise, vague, and ambiguous information retrieved from computational perception. Fuzzy set theory adopts fuzzy logic to mathematically point out uncertainty and vagueness linked with notional activities of human beings such as thinking and reasoning. Fuzzy logic encompasses flexible and robust attributes that can enable tools to overcome real-world problems with uncertain intrinsic parameters, which are approximate values rather than exact. The fuzzy logic includes some important definitions (Chukwuka et al. 2023).

1. A fuzzy set $\tilde{A}$ is a subset of a universe of discourse$X$, which is a set of ordered pairs and is characterised by a membership function $U_A\,(x)$ representing a mapping $U_A : x \rightarrow [0, 1]$. The function of $U_A\,(x)$ for the fuzzy set, A is called the membership value of x in A, which represents the degree of truth that x is an element of the fuzzy set A. It is assumed that $u_A(x)$ € $[0, 1]$, where $U_A\,(x) = 1$ reveals that x completely belongs to A, while $U_A\,(x) = 0$ indicates that x does not belong to the fuzzy set A:

$$\tilde{A} = \{\,(\,x,\ U_A\,(x)\,)\,\},\ x\ €\ X \quad (A1)$$

   where $U_A\,(x)$ is the membership function, and $X = \{x\}$ represents a collection of elements x:
2. A fuzzy number $\tilde{A}$, if it belongs to a triangular fuzzy number like Figure A1, it should satisfy the following properties:
   - $U_A\,(x) = 0$, for all x € $(-\infty, 1)$;
   - $U_A\,(x)$ is strictly increasing on $[1, m]$;

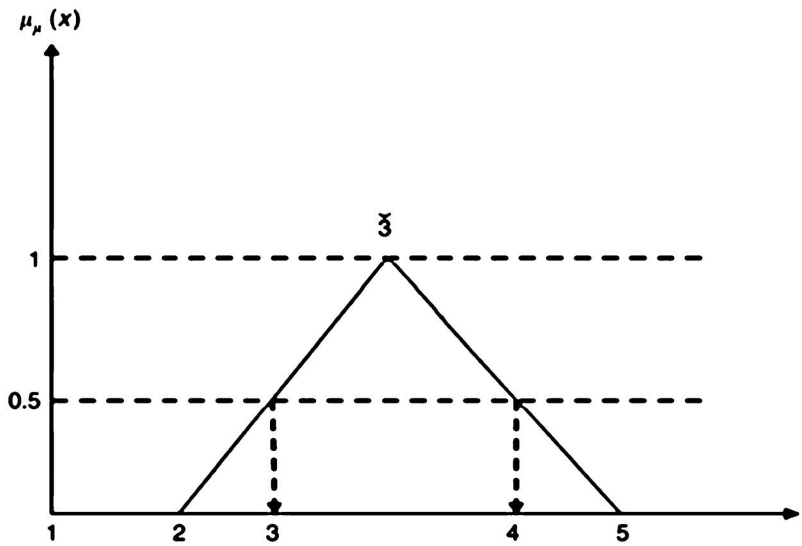

Figure A1. ∞ cut operation on a triangular fuzzy number.

- $U_A(x) = 1$, for $x = m$;
- $U_A(x)$ is strictly decreasing on $[m, u]$; and
- $U_A(x) = 0$, for all x € (u, ∞).

3. Let $\tilde{A}$ be a triangular fuzzy number (l, m, u) and its membership function can be defined as:

$$U_A(x) = \begin{cases} \frac{x-l}{m-l} & l \le x \le m \\ \frac{u-x}{u-m} & m \le x \le u \\ 0 & otherwise \end{cases} \quad (A2)$$

The α-cut of the fuzzy set $\tilde{A}$ of the universe of discourse, X is defined as:

$$A_{\propto} = \{ x \text{ € } X,\ u_A(x) \ge \propto \} \text{ where } \alpha \text{ € } [0, 1] \quad (A3)$$

Suppose $a = (a_1, a_2, a_3)$ and $b = (b_1, b_2, b_3)$ are two TFNs, the distance between them is calculated as:

$$d_v(\widetilde{a,}\ \tilde{b}) = \sqrt{\frac{1}{3}[(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2]} \quad (A4)$$

If $\tilde{A}_1 = (l_1, m_1, u_1)$ *and* $\tilde{A}_2 = (l_2, m_2, u_2)$ are representing two fuzzy triangular numbers, then algebraic operations can be expressed as follows:

$$\tilde{A}_1 (+) \tilde{A}_1 = (l_1, m_1, u_1) \text{ and } \tilde{A}_2 = (l_2, m_2, u_2) = (l_1 + l_2), (m_1 + m_2) \text{ and } \tilde{A}_2 = (u_1 + u_2) \quad (A5)$$

$$\begin{aligned} \tilde{A}_1 (-) \tilde{A}_1 &= (l_1, m_1, u_1) \text{ and } \tilde{A}_2 = (l_2, m_2, u_2) \\ &= (l_1 - l_2), (m_1 - m_2) \text{ and } \tilde{A}_2 = (u_1 - u_2) \end{aligned} \quad (A6)$$

$$\begin{aligned} \tilde{A}_1 (\times) \tilde{A}_1 &= (l_1, m_1, u_1) \text{ and } \tilde{A}_2 = (l_2, m_2, u_2) \\ &= (l_1 l_2), (m_1 m_2) \text{ and } \tilde{A}_2 = (u_1 u_2) \end{aligned} \quad (A7)$$

$$\begin{aligned} \tilde{A}_1 (/) \tilde{A}_1 &= (l_1, m_1, u_1) \text{ and } \tilde{A}_2 = (l_2, m_2, u_2) \\ &= (l_1/l_2), (m_1/m_2) \text{ and } (u_1/u_2) \end{aligned} \quad (A8)$$

$$A (\times) \tilde{A}_1 = (\propto l_1, \propto m_1, \propto u_1) \text{ where } \propto \ge 0 \quad (A9)$$

$$\tilde{A}_1^{-1} = (l_1, m_1, u_1)^{-1} = \left(\frac{1}{u_1}, \frac{1}{m_1}, \frac{1}{l_1}\right) \quad (A10)$$